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THESIS

THE EFFECTIVENESS OF HEAT EXCHANGERS
WITH ONE SHELL PASS AND
THREE TUBE PASSES

by

Mark S. O'Hare

June 1985

Thesis Advisor:

Allan D. Kraus

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The Effectiveness of Heat Exchangers
With One Shell Pass and
Three Tube Passes

by

Mark S. O'Hare
Lieutenant Commander, United States Navy
B.S., United States Naval Academy, 1976

Submitted in partial fulfillment of the
requirements for the degree of

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ABSTRACT

Heat exchangers with one shell pass and n tube passes are often referred to as 1- n exchangers. The heat transfer literature contains many references to studies of 1- n exchangers when n is even but apparently little work has been done with respect to the 1- n exchanger when n is odd. This thesis greatly expands the theoretical study of 1- n exchangers with n being odd. While a completely closed form solution was found to be unfeasible, a polynomial approximation has been developed that yields the effectiveness (ϵ) of the two possible arrangements of the 1-3 exchanger as a function of the capacity rate ratio (R) and the number of transfer units (N_{tu}). It is also shown that the effectiveness of the arrangement with two counterflow and one parallel flow tube side passes exceeds that of some of the 1- n exchangers with n even.

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NOMENCLATURE

English Letter Symbols

- A = Exchanger heat-transfer surface, sq m
- A_m = Coefficient of the mth value dimensionless
- A₀ = Coefficient, dimensionless
- A₁ = 1st order coefficient to be multiplied by N_{tu}, dimensionless
- A₂ = 2nd order coefficient to be multiplied by N_{tu}², dimensionless
- A₃ = 3rd order coefficient to be multiplied by N_{tu}³, dimensionless
- A₄ = 4th order coefficient to be multiplied by N_{tu}⁴, dimensionless
- A₅ = 5th order coefficient to be multiplied by N_{tu}⁵, dimensionless
- a = Exchanger heat-transfer surface, sq m/m
- C = Capacity rate, W°/K. Also designates dimensionless arbitrary constant
- C_{pc} = Specific heat at constant pressure of cold fluid, J/kg°K
- C_{ph} = Specific heat at constant pressure of hot fluid, J/kg°K
- D = Empirical value of effectiveness (computer generated), dimensionless
- e = Error. Also used as the exponential function
- F = Logarithmic mean temperature difference correction factor, dimensionless
- L = Exchanger length, m
- N = Number of effectiveness empirical data points used to determine a curve for R, dimensionless

n = Number of tube passes, dimensionless. Also number of equations, dimensionless
 n_c = A related N_{tu} per unit length hot side, m^{-1}
 n_h = A related N_{tu} per unit length cold side, m^{-1}
 N_{tu} = Number of transfer units, dimensionless
 P = Temperature group, dimensionless
 q = Total rate of heat transfer, W
 q_{max} = Maximum total rate of heat transfer, W
 R = Capacity rate ratio, dimensionless
 S = Temperature group, dimensionless
 S_r = Sum of the squares of the residuals, dimensionless
 T = Hot fluid temperature, °C
 T_{pi} = Particular integral, dimensionless
 T_1 = Hot fluid temperature in, °C
 T_2 = Hot fluid temperature out, °C
 t_1 = Cold fluid temperature in, °C
 t_2 = Cold fluid temperature out, °C
 t_a = Cold fluid temperature 1st pass, °C
 t_{ab} = Cold fluid temperature between 1st and 2nd passes
 t_b = Cold fluid temperature 2nd pass, °C
 t_{bc} = Cold fluid temperature between 2nd and 3rd passes
 t_c = Cold fluid temperature 3rd pass, °C
 U = Overall heat transfer coefficient, $W/m^2 - °C$
 W = Mass flow, kg/sec. Also the product of ω and L , dimensionless
 x = length coordinate, m. Also used to represent a constant value in a sequence

- y = Sum of m th degree polynomial, defined by eq. (53), dimensionless
 Z = A product of z and L , dimensionless
 z = A related N_{tu} per unit length, hot side, $1/m$

Greek Letter Symbols

- α = Root of auxiliary differential equation, $1/m$
 ϵ = Exchanger effectiveness, dimensionless
 λ = Combination of variables defined by equation (11), dimensionless
 ω = A related N_{tu} per unit length, hot side, $1/m$
 ϕ = A combination of terms defined by eq. (38), dimensionless
 Σ = Summation, dimensionless
 σ^2 = Variance, dimensionless
 θ_m = Mean temperature difference for exchanger, $^{\circ}C$
 ∂ = Indicates partial derivative, dimensionless

Subscripts

- c = Cold fluid
 h = Hot fluid
 i, j, k = Values in a sequence
 m = Degree or order, an exponent
 1 = inlet
 2 = outlet

Special Symbols

- $[A]$ = An $m \times n$ matrix, symmetric

[K] = An $m \times n$ matrix, symmetric

[L] = A lower triangular matrix

[T] = An $m \times 1$ vector

[0] = A null vector

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I. INTRODUCTION

A. BACKGROUND

When analyzing the standard counterflow heat exchanger, it becomes apparent that, from a practical standpoint, it is often difficult to obtain a high velocity for one of the fluids when this fluid is constrained to flow through all of the tubes in a single pass. This leads to a possibility of a low overall heat transfer coefficient which cancels the advantage of the high logarithmic mean temperature difference which is obtainable in true counterflow.

The quest for flow arrangements for increased heat recovery has led to arrangements that yield increased tube-side velocities and higher overall heat transfer coefficients even at the expense of a departure from the ideal true counterflow arrangement. Thus, the design may be modified so that the tube side fluid is carried through fractions of the tubes consecutively.

Heat exchangers of this type with one shell pass and n tube passes are often referred to as 1- n exchangers. These exchangers, such as the one shell pass, two-tube pass (1-2) parallel-counterflow exchanger (see Figure 1.1), are configured such that all of the tube side fluid flows through the two halves of the tubes successively. A single channel is employed with a partition to permit the

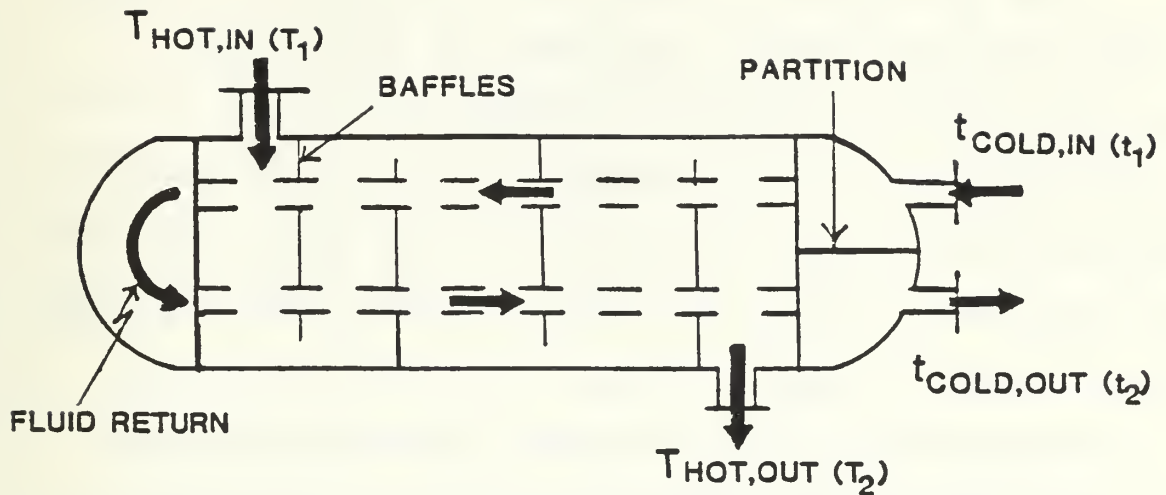


Figure 1.1 1-2 Parallel-Counterflow Exchanger

entry and exit of the tube side fluid from the same channel. Note the baffles used to induce turbulence causing the liquid to flow through the shell at right angles to the axes of the tubes thus helping to create a higher shell side velocity with higher shell side heat-transfer coefficients.

To date, much work has been done on finding the true logarithmic mean temperature difference for heat exchangers with an even number of tube passes. Little work, however, has been done with regard to heat exchangers having an odd number of passes. This is primarily due to the method employed in deriving an analytical solution to measure the overall effectiveness of a heat exchanger.

Exchangers with an even number of tube passes often present a configuration problem especially in a marine application where the inlet and outlet of the cooling fluid must

be one the same side of the exchanger header (see Figure 1.1). This particular problem could be alleviated by going to heat exchangers with an odd number of tube passes. Currently, precise mathematical expressions for the effectiveness of the 1-3 exchangers do not exist. Hence, a theoretical examination is reported on here which considers the effectiveness of the 1-3 parallel-counter flow exchanger which is shown in Figure 1.2.

Before doing this it is important to mention the work that lead to the effectiveness method and the development of work on heat exchangers with an odd number of tube passes.

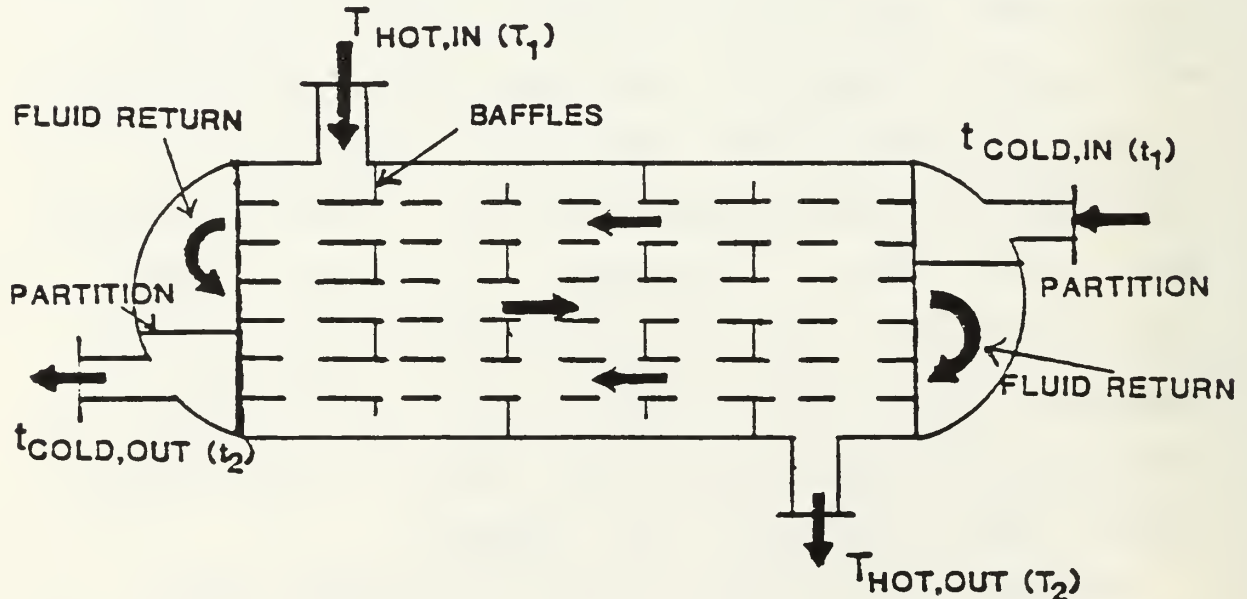


Figure 1.2 1-3 One Shell Pass Three Tube Pass Exchanger

This will be considered in Section II. Kern [Ref. 1: pp. 224-226], makes the interesting point that the optimum exchanger requires an exchanger capable of providing the optimum fluid-flow velocities on the shell as well as the tube sides. This might frequently entail the use of an odd number of tube passes or an odd tube length.

B. WHY EFFECTIVENESS AS A FUNCTION OF N_{tu}

It is also noted that Kays and London [Ref. 2: pp. 24-29] indicated that the effectiveness as a function of N_{tu} ($\epsilon - N_{tu}$) method is the favored approach for evaluating a heat exchanger's performance because:

1. The effectiveness value stands alone as a dependent variable and should not appear directly in the abscissa and indirectly in the ordinate of a graphical display.
2. The log-mean difference equation misleadingly simplifies the notion of what is involved in heat exchanger design theory, since the implication is that only a rate equation is required.
3. The $\epsilon - N_{tu}$ approach simplifies the algebra involved in predicting the performance of complex flow arrangements.
4. The more meaningful arguments are related to ease of use in design work. Two prime examples of these are:
 - a) Given the overall heat transfer coefficient, U , the two fluid capacity rates, C_c and C_h , and the terminal temperatures, determine the required surface area, A .
 - b) Given A , U , C_c , C_h and the inlet temperatures of both streams, determine the outlet temperatures.

II. THE DEVELOPMENT OF THE EFFECTIVENESS METHOD

A. LITERATURE SURVEY

It was Nagle [Ref. 3: pp. 604-609], in 1931, who credited Davis [Ref. 4] with a simplified method for computing actual temperature differences between two heat-interchanging streams which depart from true counter or concurrent (parallel) flow. This is now the familiar "F factor" method which expresses the actual mean temperature difference θ_m in $q = UA \theta_m$ as a fraction F of the counterflow logarithmic mean temperature difference, LTMD, θ_{mc} via $\theta_m = F \theta_{mc}$.

The example of initial interest was the 1-2 exchanger with a single shell pass and two continuous tube passes in counter and concurrent flow with it. The method involved derivation of the actual temperature difference for the flow pattern and formed the ratio $F = \theta_m / \theta_{mc}$. This familiar LMTD correction factor was plotted conveniently as functions of the effectiveness, ϵ , and the capacity rate ratio R with R as a parameter. These mean temperature difference correction charts are available for many flow arrangements [Ref. 1: pp. 829-833 and Ref. 5]. The effectiveness, ϵ (often called P or S), is always the cold fluid effectiveness and R is always the capacity rate ratio of cold fluid to hot fluid.

Nagle detailed assumptions and derivations for the 1-2, 1-4 and 1-6 exchangers. The F factors were obtained by Nagle through graphical integration and were accompanied by the comment that F factors for the 1-2 exchanger could be applied with negligible error to 1-4 and 1-6 exchangers. Underwood [Ref. 6: pp. 145-148] rederived the equations of Nagle for 1-2 and 1-4 exchangers to eliminate the need for obtaining F factors by graphical integration.

Bowman [Ref. 7: pp. 541-544] pointed out that for a very large or infinite number of tube passes, the F factor approached, as a limit, its value in crossflow with both fluids completely mixed. It was further stated that even at the limit, the F factors were only 1 to 2 percent lower than those for the 1-2 exchanger. A previous paper by Kraus and Kern [Ref. 8] did not confirm the generalization that 1-n exchangers differed only negligibly from the 1-2 exchanger although this lack of confirmation was obtained on an $\epsilon = f(R, N_{tu})$ basis. Moreover, the Kraus-Kern work does not confirm the generalizations on an $F = f(R, N_{tu}, \epsilon)$ basis.

From the standpoint of usefulness and good accuracy, it is essential that F factors, if they are to be used in preference to $\epsilon = f(R, N_{tu}, \text{flow arrangement})$, be obtained with precision. Plots of $F = f(R, \epsilon, = P \text{ or } S)$ [Ref. 1: pp. 829-833 and Ref. 5] show that the curves for particular values of R approach infinite slope as F decreases. While this can be partially alleviated by restricting $R < 1.0$ (a

constraint used in the $\epsilon = f(R, N_{tu}, \text{flow arrangement})$ approach), it is seen that small errors in the interpolation for R or $\epsilon = P$ or S can result in large fluctuations in the value of F .

In a comprehensive paper, Bowman, Mueller and Nagle [Ref. 9: pp. 283-294] presented graphs of F factors for shells with one through six shell passes and numbers of continuous tube passes respectively double the number of shell passes. In view of the earlier references to Nagle and Bowman, it should be noted that F factors were computed for the 1-2 exchanger in [Ref. 9: pp. 283-294] using the equations of Underwood [Ref. 6: pp. 145-158].

Ten Broeck [Ref. 10: pp. 1041-1042] prepared a graph of the dimensionless groups now known as ϵ , R and N_{tu} for the 1-2 exchanger. Such a graph had the added versatility of simplifying the calculation of performance in a given exchanger when operating at conditions different for those for which it was designed. Kays and London [Ref. 2: pp. 63-74] prepared similar graphs and tables of $\epsilon = f(R, N_{tu}, \text{flow arrangement})$ for the 1-2 exchanger and for several cases of crossflow and periodic flow.

The foregoing describes the early history of the search for the so-called Logarithmic Mean Temperature Difference Correction Factor, F , with regard to heat exchangers having an even number of tube passes. It is a fact, however, that certain space economies could be realized from exchangers

having an odd number of tube passes so that the tube side fluid could enter and leave the exchanger at opposite ends of the exchanger (see Figure 1.2).

B. FISCHER'S WORK

With the foregoing in mind, an extensive search has been conducted to obtain $\epsilon - N_{tu}$ data for the so called "1-3" and "1-5" exchangers. This search has uncovered a single work, that of Fischer [Ref. 11: pp. 377-383], which summarizes the historical development covered here and contains only a small section on the 1-3 exchanger. This work by Fischer develops an equation for true mean temperature difference of the 1-3 exchanger and casts the results in terms of F rather than ϵ . Moreover, the work treats only the case where the three tube passes are arranged with two in counterflow and one in parallel flow (1-3:2C) making no mention of the one counterflow and two parallel flow (1-3:2P) case (see Figures 2.1 and 2.2). In addition, the equation developed to yield F must be solved using a trial and error solution.

The present work is aimed at continuing the Fischer investigation for several reasons:

1. A solution is needed for effectiveness, ϵ , as a function of capacity rate (R) and number of transfer units (N_{tu}).
2. This solution should be in a closed form if at all possible so that it will be computationally efficient and useful in both the design and analysis frameworks.

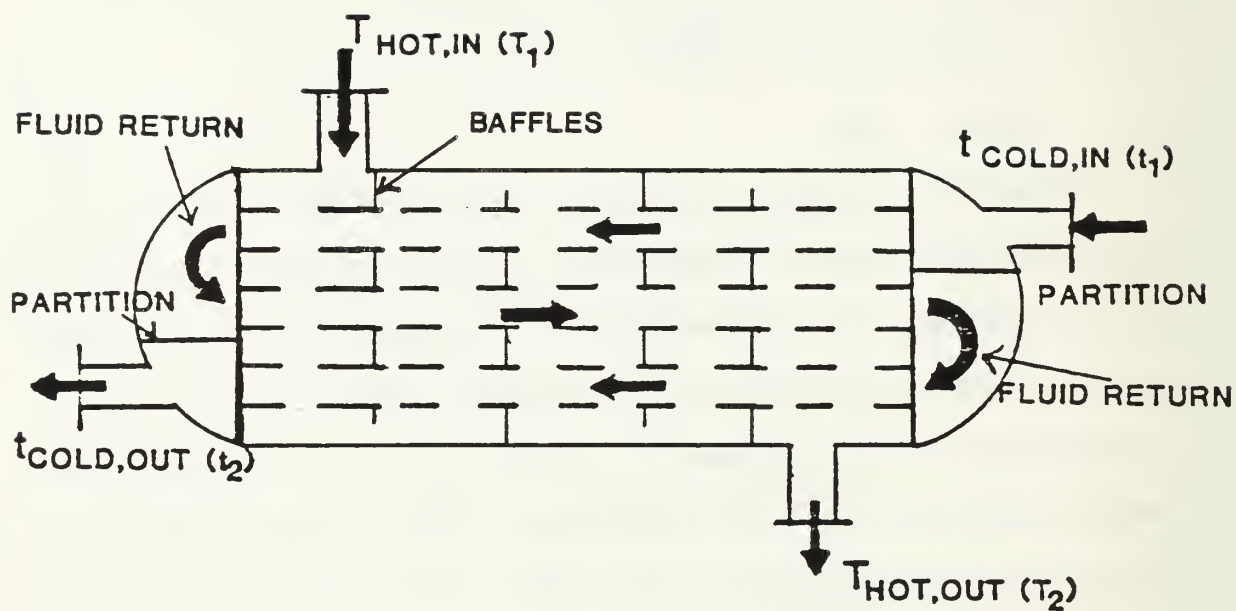


Figure 2.1 1-3:2C Three Tube Passes - Two in Counterflow

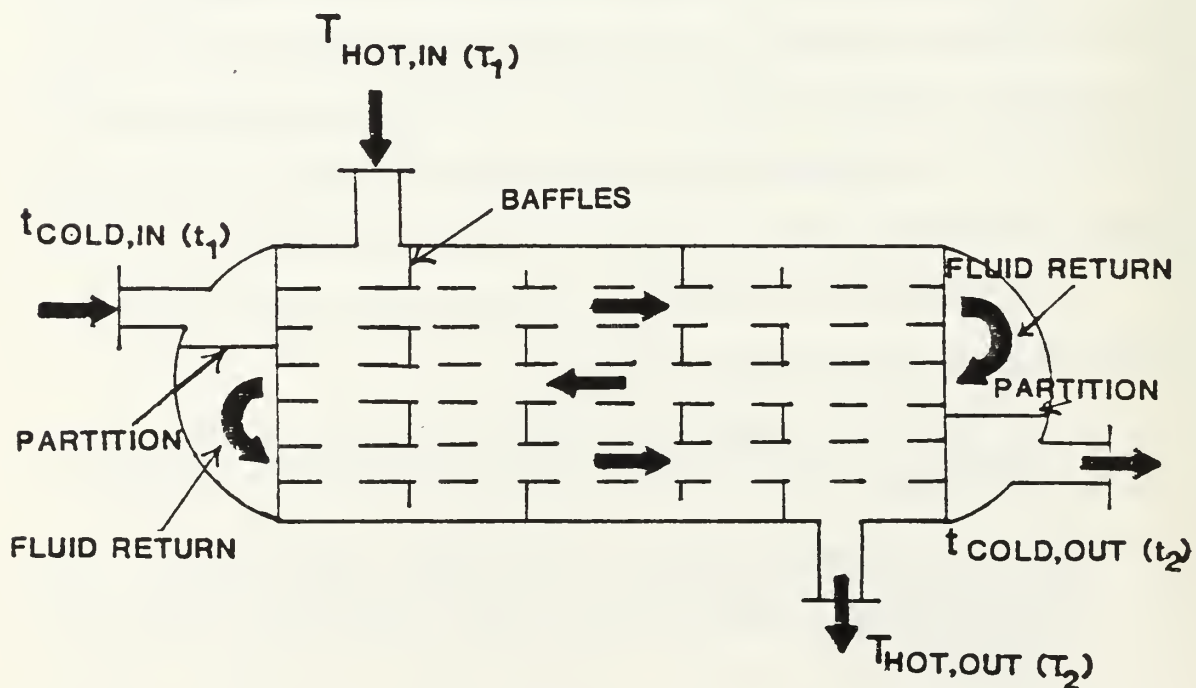


Figure 2.2 1-3:2P Three Tube Passes - Two in Parallel Flow

3. Because valid design data can evolve from a polynomial approximation. The search should not be abandoned just because a closed form solution does not result from an analytical approach.
4. Data is needed for the (1-3:2P) two parallel-one counterflow configuration.
5. A 1-3 exchanger in a marine (shipboard) application may result in a considerable space saving over its 1-n counterpart with n even. This would be evident on the outside of the exchanger where it would be immediately noted that the 1-3 exchanger has tube side inlet and outlet at opposite ends of the exchanger.

The next section confirms Fischer's result and shows that a closed form solution cannot be obtained for the effectiveness of the 1-3 exchanger. Sections IV and V demonstrate how, through numerical analysis assisted by a computer, a polynomial solution can be derived that will yield the effectiveness to engineering accuracy.

III. AN ATTEMPT AT A CLOSED FORM SOLUTION

A. EFFECTIVENESS AS A FUNCTION OF CAPACITY RATES AND EXCHANGER SIZE

This section deals with an investigation into the effectiveness, ϵ , of a one shell pass and three tube pass heat exchanger, whereby ϵ compares the actual heat transfer rate to the thermodynamically limited, maximum possible heat transfer rate as would be realized only in a counter flow heat exchanger of infinite transfer area. This exchanger heat transfer effectiveness is given by

$$\epsilon = \frac{q}{q_{\max}} = \frac{C_h(T_{\text{hot,in}} - T_{\text{hot,out}})}{C_{\min}(T_{\text{hot,in}} - t_{\text{cold,in}})} = \frac{C_c(t_{\text{cold,out}} - t_{\text{cold,in}})}{C_{\min}(T_{\text{hot,in}} - t_{\text{cold,in}})}$$

where C_{\min} is the smaller of the C_h and C_c magnitudes.

Thus, ϵ possesses the significance of effectiveness of the heat exchanger from a thermodynamic point of view, with the magnitude of the effectiveness completely defining the heat transfer performance. In general we express $\epsilon = f(N_{tu}, R, \text{and flow arrangement})$ and when the flow arrangement is understood, it is said that $\epsilon = f(N_{tu}, R)$. [Ref. 2: pp. 14-26].

The number of heat transfer units N_{tu} is a nondimensional expression of the "heat transfer size" of the exchanger.

When N_{tu} is small the exchanger effectiveness is low, and when N_{tu} is large, ϵ approaches the limit imposed by the flow

arrangement and thermodynamic conditions asymptotically.

From inspection of the definition of N_{tu}

$$N_{tu} = \frac{AU}{C_{\min}} = \frac{1}{C_{\min}} \int_0^A U dA$$

it is clear that the overall conductance and transfer area affect the costs of attaining a high value for N_{tu} , ergo high ϵ . The capacity rate ratio, R , as defined by

$$R = \frac{C_{\min}}{C_{\max}}$$

is simply the ratio of mass flow rate times specific heat capacity for the two streams. These can be considered as flow stream thermal-capacity rates, i.e., energy storage rate in the stream per unit of temperature change. [Ref. 2: pp. 14-26]

The attempt taken in this thesis to develop a closed form solution has used the basic fundamentals of heat transfer as well as those indicated above. A closed form solution for ϵ was sought for both 1-3 exchangers with one having two out of three tube passes in parallel flow and the other having two out of three tube passes in counterflow. The analytical approach taken, and demonstrated in this section, is for two out of three tube passes in counterflow.

B. ANALYTICAL DEVELOPMENT

The derivation for the effectiveness, ϵ , of the 1-3 exchanger as a function of the capacity rate ratio, R , and number of transfer units, N_{tu} , depends on several assumptions.

- (1) The overall coefficient of heat transfer, U , does not vary within the exchanger.
- (2) The specific heat of both hot side and cold side fluids does not vary.
- (3) Each fluid is thoroughly mixed, that is, the temperature of both hot and cold side fluids is uniform over any cross section.
- (4) Steady flow conditions are maintained.
- (5) Heat losses to or from the environment are negligible.
- (6) No change of phase takes place; all heat transferred is sensible heat.
- (7) There is equal heat transfer surface in each pass.

The configuration is shown in Figure 3.1 where the three tube passes are designated with subscripts a, b and c. The temperature of the hot (shell side) fluid is indicated by upper case letters. For the cold (tube side) fluid, lower case letters are used. The subscript 1 always refers to the fluid inlet and the subscript 2 always refers to the fluid outlet.

With W_h and C_{ph} designating mass flow (kg/sec) and specific heat (Joules/kg $^{\circ}$ K) of hot fluid entering at T_1 and leaving at T_2 we define a capacity rate for the hot side

$$C_h = W_h C_{ph}$$

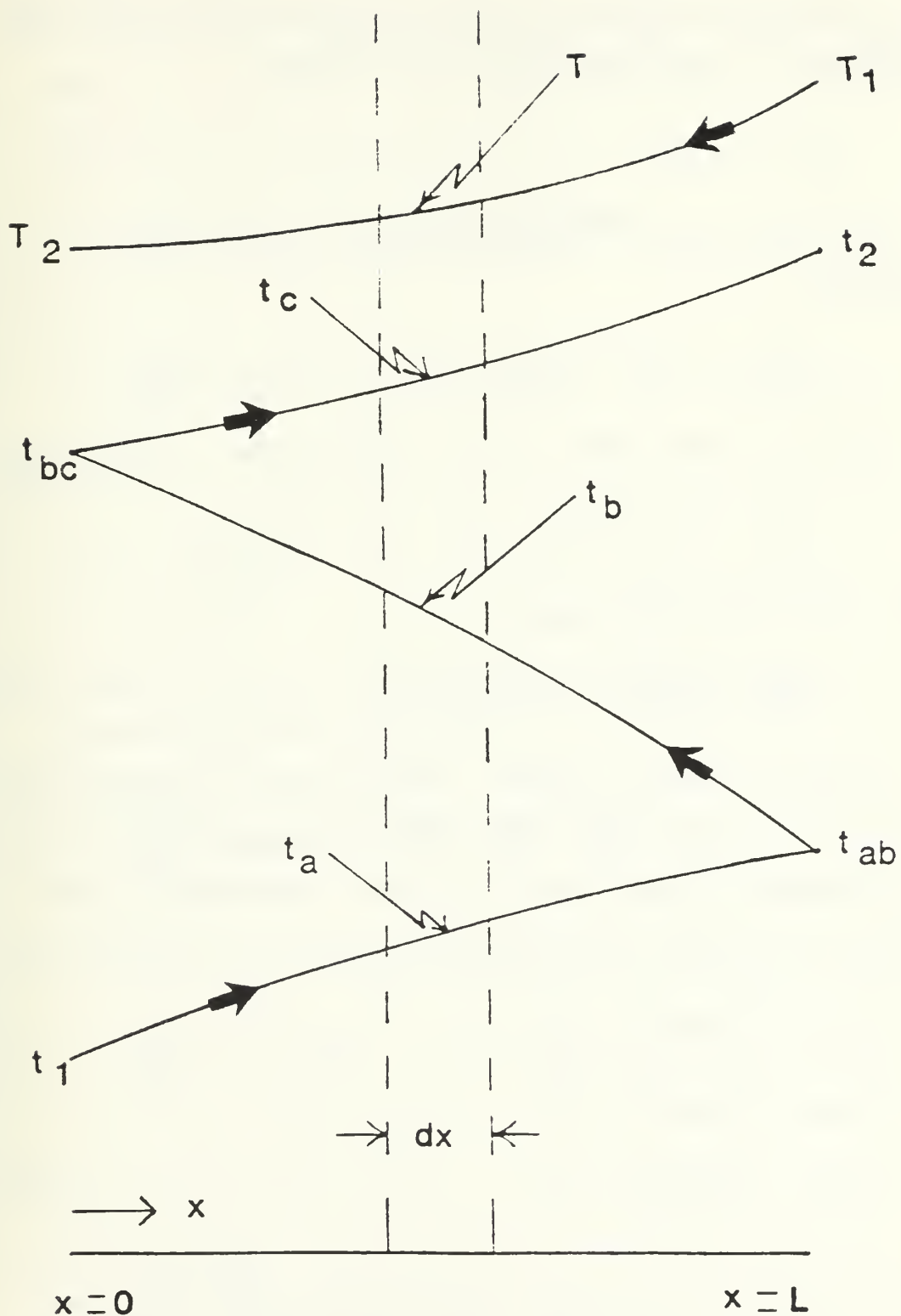


Figure 3.1 Two Counter One Parallel Configuration for Development of Effectiveness Relationship

In similar fashion for the cold side (with W_c and C_{pc}) entering at t_1 and leaving at t_2 , we have

$$C_c = W_c C_{pc}$$

We then obtain an energy balance for the entire exchanger

$$C_h(T_1 - T_2) = C_c(t_2 - t_1) \quad (1)$$

Over the right hand side of the exchanger (Figure 3.1)

$$C_h(T_1 - T) = C_c(t_2 - t_c + t_b - t_a) \quad (2)$$

and a differentiation gives

$$C_h dT = C_c(dt_c - dt_b + dt_a) \quad (3)$$

Across dx , with a (m^2/m), the surface per running meter of length of pass so that $A = 3aL$ is the total surface in the exchanger, we may write the heat transferred to the element dx in each cold pass.

$$C_c dt_a = Ua dx (T - t_a) \quad (4a)$$

$$C_c dt_b = -Ua dx (T - t_b) \quad (4b)$$

$$C_c dt_c = Ua dx (T - t_c) \quad (4c)$$

Here it should be observed that due cognizance has been taken of the direction of the flow in each cold fluid pass

with respect to the positive sense of the length coordinate, x , and U is the overall heat transfer coefficient ($\text{W/m}^2\text{-}^\circ\text{C}$).

With eqs. (4) in eq. (3)

$$C_h dT = Ua(3T - t_a - t_b - t_c)dx$$

or

$$\frac{dT}{dx} = n_h(3T - t_a - t_b - t_c) \quad (5)$$

where

$$n_h = \frac{Ua}{C_h}$$

is a sort of N_{tu} per unit length for the hot side.

Now differentiate eq. (5)

$$\frac{d^2T}{dx^2} = n_h \left(3 \frac{dT}{dx} - \frac{dt_a}{dx} - \frac{dt_b}{dx} - \frac{dt_c}{dx} \right)$$

and with eqs. (4) substituted

$$\frac{d^2T}{dx^2} = 3n_h \frac{dT}{dx} - n_c n_h (T - t_a + t_b - t_c) \quad (6)$$

where

$$n_c = \frac{Ua}{C_c}$$

where again the resemblance of n_c to N_{tu} can be noted.

From eq. (2) we obtain

$$\frac{C_h}{C_c} (T_1 - T) - t_2 = t_b - t_a - t_c \quad (7)$$

and with eq. (7) put into eq. (6) we obtain

$$\frac{d^2 T}{dx^2} - 3n_h \frac{dT}{dx} = -n_c n_h \left[T + \frac{C_h}{C_c} (T_1 - T) - t_2 \right]$$

or

$$\frac{d^2 T}{dx^2} - 3n_h \frac{dT}{dx} = -n_c n_h \frac{C_h}{C_c} [(R_c - 1)T + T_1 - R_c t_2] \quad (8)$$

where

$$R_c = C_c / C_h$$

is the capacity rate ratio for the cold side.

Notice that

$$n_c n_h \frac{C_h}{C_c} = \frac{U_a}{C_c} \cdot \frac{U_a}{C_h} \cdot \frac{C_h}{C_c} = \left(\frac{U_a}{C_c} \right)^2 = m$$

and

$$R_h = \frac{1}{R_c} = \frac{C_h}{C_c}$$

a capacity rate ratio for the hot side. Then, algebraic adjustment provides

$$\frac{d^2 T}{dx^2} - 3n_h \frac{dT}{dx} + m \left(\frac{1 - R_h}{R_h} \right) T = m \left(\frac{t_2}{R_h} - T_1 \right) \quad (9)$$

which is a linear, non-homogeneous, second order differential equation with constant coefficients having a complementary function

$$T_c = C_1 e^{\alpha_1 x} + C_2 e^{\alpha_2 x} \quad (10)$$

where C_1 and C_2 are arbitrary constants and where

$$\begin{aligned} \alpha_1, \alpha_2 &= \frac{3n_h}{2} \pm \frac{1}{2} \left[9n_h^2 - 4m \left(\frac{1 - R_h}{R_h} \right) \right]^{1/2} \\ &= \frac{3n_h}{2} \pm \frac{n_h}{2} \left[9 - \frac{4m}{n_h} \left(\frac{1 - R_h}{R_h} \right) \right]^{1/2} \end{aligned}$$

But

$$\frac{m}{n_h^2} = \frac{(Ua)^2}{(C_c)^2} \cdot \frac{(C_h)^2}{(Ua)^2} = \left(\frac{C_h}{C_c} \right)^2 = R_h^2 = \frac{1}{R_c^2}$$

so that

$$\alpha_1, \alpha_2 = \frac{3n_h}{2} \pm \frac{n_h}{2} \left[9 - 4R_h^2 \left(\frac{1 - R_h}{R_h} \right) \right]^{1/2}$$

or

$$\alpha_1, \alpha_2 = \frac{n_h}{2} (3 \pm \lambda) \quad (11)$$

where

$$\lambda = [9 - 4R_h(1 - R_h)]^{1/2} \quad (12)$$

Designate the particular integral as T_{pi} and by the method of undetermined coefficients let $T_{pi} = P$ so that in eq. (9)

$$m\left(\frac{1 - R_h}{R_h}\right) P = m\left(\frac{t_2}{R_h} - T_1\right)$$

This makes

$$T_{pi} = P = \left[\frac{t_2}{R_h} - T_1 \right] \left[\frac{R_h}{1 - R_h} \right]$$

so that

$$T_{pi} = \frac{t_2 - R_h T_1}{1 - R_h} \quad (13)$$

The general solution to eq. (9) is the sum of eqs. (10) and (13)

$$T(x) = C_1 e^{\alpha_1 x} + C_2 e^{\alpha_2 x} + \frac{t_2 - R_h T_1}{1 - R_h} \quad (14)$$

where the arbitrary constants, C_1 and C_2 are evaluated from conditions at $x = 0$ and $x = L$. At $x = 0$, $T(x = 0) = T_2$ and at $x = L$, $T(x = L) = T_1$. When these are inserted, in turn, into eq. (14), one obtains a pair of linear algebraic equations in the unknowns C_1 and C_2

$$T_2 = C_1 + C_2 + T_{pi}$$

$$T_1 = C_1 e^{\alpha_1 L} + C_2 e^{\alpha_2 L} + T_{pi}$$

where T_{pi} is given by eq. (13).

It is only a matter of algebra to show that

$$C_1 = \frac{(T_1 - T_{pi}) - (T_2 - T_{pi})e^{\alpha_2 L}}{e^{\alpha_1 L} - e^{\alpha_2 L}} \quad (15a)$$

and

$$C_2 = \frac{(T_2 - T_{pi})e^{\alpha_1 L} - (T_1 - T_{pi})}{e^{\alpha_1 L} - e^{\alpha_2 L}} \quad (15b)$$

It is easy to see from eq. (1) that

$$R_h = \frac{C_h}{C_c} = \frac{(t_2 - t_1)}{(T_1 - T_2)}$$

so that

$$t_2 = t_1 + R_h(T_1 - T_2)$$

Use of this in eq. (13) shows that

$$T_{pi} = \frac{t_1 + R_h(T_1 - T_2) - R_h T_1}{1 - R_h}$$

or

$$T_{pi} = \frac{t_1 - R_h T_2}{1 - R_h} \quad (16)$$

indicating two alternative forms for T_{pi} given by eqs. (13) and (16).

Insertion of eqs. (13) and (16) in eqs. (15) for C_1 and C_2 will yield after some algebra

$$C_1 = \frac{\left(\frac{T_1 - t_2}{1 - R_h}\right) - \left(\frac{T_2 - t_1}{1 - R_h}\right) e^{\alpha_2 L}}{e^{\alpha_1 L} - e^{\alpha_2 L}} \quad (17a)$$

and

$$C_2 = \frac{\left(\frac{T_2 - t_1}{1 - R_h}\right) e^{\alpha_1 L} - \left(\frac{T_1 - t_2}{1 - R_h}\right)}{e^{\alpha_1 L} - e^{\alpha_2 L}} \quad (17b)$$

Equation (14) is an expression for the hot side temperature at any location in the exchanger in terms of the extreme temperatures, t_1 , t_2 , T_1 and T_2 .

Next take eq. (5) and set it equal to the derivative of eq. (14) noting that C_1 , C_2 and T_{pi} are all known constants.

$$\frac{dT}{dx} = n_h (3T - t_a - t_b - t_c) = \alpha_1 C_1 e^{\alpha_1 x} + \alpha_2 C_2 e^{\alpha_2 x} \quad (18)$$

At $x = 0$, where $T = T_2$, $t_a = t_1$ and $t_b = t_c = t_{hc}$

$$\frac{dT}{dx} = n_h(3T_2 - t_1 - 2t_{bc}) = \alpha_1 C_1 + \alpha_2 C_2 \quad (19)$$

and if we subtract eq. (4a) from eq. (4c) we obtain

$$\frac{dt_a - dt_c}{t_a - t_c} = -\frac{U_a}{C_c} dx = -n_c dx$$

which can be integrated using C_3 as the constant of integration.

$$t_a - t_c = C_3 e^{-n_c x}$$

and at $x = 0$ where $t_a = t_1$ and $t_c = t_{bc}$

$$t_1 - t_{bc} = C_3$$

or

$$t_{bc} = t_1 - C_3$$

In addition at $x = L$, $t_a = t_{ab}$ and $t_c = t_2$ so that

$$t_{ab} - t_2 = C_3 e^{n_c L}$$

or

$$C_3 = \frac{t_{ab} - t_2}{e^{-n_c L}} = (t_{ab} - t_2) e^{n_c L}$$

This gives a relationship between t_{ab} and t_{bc}

$$t_{bc} = t_1 - (t_{ab} - t_2) e^{n_c L} \quad (20)$$

where $N_c = n_c L$ can be considered as the total number of transfer units for the cold side.

Return now to eq. (18) and look at the conditions at $x = L$ where $t_a = t_b = t_{ab}$, $t_c = t_2$ and $T = T_1$. These conditions in eq. (18) give

$$n_h(3T_1 - 2t_{ab} - t_2) = \alpha_1 C_1 e^{\alpha_1 L} + \alpha_2 C_2 e^{\alpha_2 L}$$

where again we remember that C_1 and C_2 are known constants. Solving for t_{ab}

$$2t_{ab} = -\frac{1}{n_h} (\alpha_1 C_1 e^{\alpha_1 L} + \alpha_2 C_2 e^{\alpha_2 L}) + 3T_1 - t_2$$

and with this in eq. (20)

$$2t_{bc} = e^{N_c} \left[\frac{1}{n_h} (\alpha_1 C_1 e^{\alpha_1 L} + \alpha_2 C_2 e^{\alpha_2 L}) + 3t_2 - 3T_1 \right] + 2t_1$$

Then with eq. (21) in eq. (19)

$$\alpha_1 C_1 + \alpha_2 C_2 = 3n_h [(T_2 - t_1) + e^{N_c}(T_1 - t_2)] - e^{N_c} (\alpha_1 C_1 e^{\alpha_1 L} + \alpha_2 C_2 e^{\alpha_2 L}) \quad (22)$$

Equation (22) confirms Fischer's result [Ref. 12: pp. 377-383] and at this point in his development he branches off to seek an expression for the Logarithmic Mean

Temperature Difference Correction Factor, F. The attention here is focused on $\epsilon = f(R, N_{tu})$ and the balance of this section continues in this vein.

Look at the $\alpha_1 C_1 + \alpha_2 C_2$ term in eq. (22). Use of eq. (11) allows the representation of $\alpha_1 C_1 + \alpha_2 C_2$

$$\frac{n_h}{2} (3 + \lambda) C_1 + \frac{n_h}{2} (3 - \lambda) C_2 \quad (23a)$$

or

$$\frac{3n_h}{2} (C_1 + C_2) + \frac{\lambda n_h}{2} (C_1 - C_2) \quad (23b)$$

Then from eqs. (17)

$$C_1 + C_2 = \frac{(T_2 - t_1)[e^{\alpha_1 L} - e^{\alpha_2 L}]}{(1 - R_h)[e^{\alpha_1 L} - e^{\alpha_2 L}]}$$

or

$$C_1 + C_2 = \frac{T_2 - t_1}{1 - R_h} \quad (24)$$

Moreover

$$C_1 - C_2 = \frac{2(T_1 - t_2) - (T_2 - t_1)[e^{\alpha_1 L} + e^{\alpha_2 L}]}{(1 - R_h)[e^{\alpha_1 L} - e^{\alpha_2 L}]} \quad (25)$$

Now let

$$\omega = \frac{3n_h}{2} \quad (26a)$$

and

$$z = \frac{\lambda n_h}{2} \quad (26b)$$

so that

$$\begin{aligned} e^{\alpha_1 L} - e^{\alpha_2 L} &= e^{(\omega+z)L} - e^{(\omega-z)L} \\ &= e^{\omega L} e^{zL} - e^{\omega L} e^{-zL} \\ &= e^{\omega L} (e^{zL} - e^{-zL}) \end{aligned}$$

or

$$e^{\alpha_1 L} - e^{\alpha_2 L} = 2e^{\omega L} \sinh zL \quad (27)$$

Moreover, it is easy to see that

$$e^{\alpha_1 L} + e^{\alpha_2 L} = 2e^{\omega L} \cosh zL \quad (28)$$

If eqs. (24) through (28) are collected and put into the expression of eq. (23b), the result is

$$\alpha_1 C_1 + \alpha_2 C_2 = \frac{3n_h}{2} (C_1 + C_2) + \frac{\lambda n_h}{2} (C_1 - C_2) \quad (23b)$$

$$= \omega \left[\frac{T_2 - t_1}{1 - R_h} \right] + z \left[\frac{2(T_1 - t_2) - (T_2 - t_1)2e^{\omega L} \operatorname{csch} zL}{(1 - R_h)2e^{\omega L} \sinh zL} \right]$$

or

$$\alpha_1 C_1 + \alpha_2 C_2 = \omega \left(\frac{T_2 - t_1}{1 - R_h} \right) + z \left[\left(\frac{T_1 - t_2}{1 - R_h} \right) e^{-\omega L} \operatorname{csch} zL - \left(\frac{T_2 - t_1}{1 - R_h} \right) \coth zL \right] \quad (29a)$$

and this could also be written as

$$\alpha_1 C_1 + \alpha_2 C_2 = \left(\frac{T_2 - t_1}{1 - R_h} \right) [\omega - z \coth zL] + z \left(\frac{T_1 - t_2}{1 - R_h} \right) e^{-\omega L} \operatorname{csch} zL \quad (29b)$$

The next step is to reduce the right hand side of eq.

(22). Use of eq. (11) permits the representation

$$\alpha_1 C_1 e^{\alpha_1 L} + \alpha_2 C_2 e^{\alpha_2 L} = \left(\frac{3n_h}{2} + \frac{\lambda n_h}{2} \right) C_1 e^{\alpha_1 L} + \left(\frac{3n_h}{2} - \frac{\lambda n_h}{2} \right) C_2 e^{\alpha_1 L}$$

or with eqs. (26) inserted

$$\alpha_1 C_1 e^{\alpha_1 L} + \alpha_2 C_2 e^{\alpha_2 L} = \omega (C_1 e^{\alpha_1 L} + C_2 e^{\alpha_2 L}) + z (C_1 e^{\alpha_1 L} - C_2 e^{\alpha_2 L}) \quad (30)$$

But by eqs. (11) and (17)

$$C_1 e^{\alpha_1 L} + C_2 e^{\alpha_2 L} = \frac{(T_1 - t_2)(e^{\alpha_1 L} - e^{\alpha_2 L}) + (T_2 - t_1)[e^{(\alpha_1 + \alpha_2)L} - e^{(\alpha_1 + \alpha_2)L}]}{(1 - R_h)(e^{\alpha_1 L} - e^{\alpha_2 L})}$$

or

$$C_1 e^{\alpha_1 L} + C_2 e^{\alpha_2 L} = \frac{T_1 - t_2}{1 - R_h} \quad (31)$$

$C_1 e^{\alpha_1 L} - C_2 e^{\alpha_2 L}$ may also be simplified. Again using

eqs. (11), (17a) and (17b)

$$C_1 e^{\alpha_1 L} - C_2 e^{\alpha_2 L} = \frac{(T_1 - t_2)(e^{\alpha_1 L} + e^{\alpha_2 L}) - (T_2 - t_1)[e^{(\alpha_1 + \alpha_2)L} + e^{(\alpha_1 + \alpha_2)L}]}{(1 - R_h)(e^{\alpha_1 L} - e^{\alpha_2 L})}$$

The exponential term at the far right in the numerator is really quite simple. From eq. (11)

$$\alpha_1 + \alpha_2 = \left(\frac{3n_h}{2} + \frac{\lambda n_h}{2} \right) + \left(\frac{3n_h}{2} - \frac{\lambda n_h}{2} \right) = 3n_h$$

and by eq. (26a) $\alpha_1 + \alpha_2 = 3n_h = 2\omega$. Thus with the combination of exponentials in the numerator and the denominator given by eqs. (27) and (28) we find that

$$C_1 e^{\alpha_1 L} - C_2 e^{\alpha_2 L} = \frac{2(T_1 - t_2)e^{\omega L} \cosh zL - (T_2 - t_1)2e^{2\omega L}}{2(1 - R_h)e^{\omega L} \sinh zL}$$

or

$$C_1 e^{\alpha_1 L} - C_2 e^{\alpha_2 L} = \left(\frac{T_1 - t_2}{1 - R_h} \right) \coth zL - \left(\frac{T_2 - t_1}{1 - R_h} \right) e^{\omega L} \operatorname{csch} zL \quad (32)$$

Now with eqs. (31) and (32) put into eq. (30) we obtain

$$\alpha_1 C_1 e^{\alpha_1 L} + \alpha_2 C_2 e^{\alpha_2 L} = \omega \left(\frac{T_1 - t_2}{1 - R_h} \right) + z \left[\left(\frac{T_1 - t_2}{1 - R_h} \right) \coth zL - \left(\frac{T_2 - t_1}{1 - R_h} \right) e^{\omega L} \operatorname{csch} zL \right]$$

or

$$\alpha_1 C_1 e^{\alpha_1 L} + \alpha_2 C_2 e^{\alpha_2 L} = \left(\frac{T_1 - t_2}{1 - R_h} \right) [\omega + z \coth zL] - z \left(\frac{T_2 - t_1}{1 - R_h} \right) e^{\omega L} \operatorname{csch} zL \quad (33)$$

With eqs. (29b) and (33) inserted into eq. (22) we obtain

$$\left(\frac{T_2 - t_1}{1 - R_h} \right) [\omega - z \coth zL] + z \left(\frac{T_1 - t_2}{1 - R_h} \right) e^{-\omega L} \operatorname{csch} zL =$$

$$3n_h [(T_2 - t_1) + e^{N_c} (T_1 - t_2) -$$

$$e^{-N_c} \left(\frac{T_1 - t_2}{1 - R_h} \right) (\omega + z \coth zL) - z \left(\frac{T_2 - t_1}{1 - R_h} \right) e^{\omega L} \operatorname{csch} zL] \quad (34)$$

We wish to develop an expression for the exchanger effectiveness so we designate the hot side effectiveness as

$$\epsilon_h = \frac{T_1 - T_2}{T_1 - t_1} \quad (35)$$

and we begin by simplifying eq. (34) by dividing throughout by $(T_2 - t_1)/(1 - R_h)$ to obtain

$$\begin{aligned} (\omega - z \coth Z) + ze^{-W} \operatorname{csch} z \left(\frac{T_1 - t_2}{T_2 - t_1} \right) &= R + e^{N_c R} \left(\frac{T_1 - t_2}{T_2 - t_1} \right) \\ - e^{-N_c} [(\omega + z \coth Z) \left(\frac{T_1 - t_2}{T_2 - t_1} \right) - ze^W \operatorname{csch} Z] &\quad (36) \end{aligned}$$

where

$$W = \omega L \quad (37a)$$

$$Z = zL \quad (37b)$$

and

$$R = 3n_h(1 - R_h) \quad (37c)$$

We can then let

$$\phi = \frac{T_1 - t_2}{T_2 - t_1}$$

and get eq. (36) to look like

$$(\omega - z \coth Z) + (ze^{-W} \operatorname{csch} Z) \phi =$$

$$R + (e^{N_c} R) \phi - [e^{-N_c} (\omega + \coth Z)] \phi - (ze^{(W-N_c)} \operatorname{csch} Z)$$

It is now a matter of algebra to solve for ϕ

$$\phi = \frac{R + ze^{(W-N_c)} \operatorname{csch} Z - (\omega - z \coth Z)}{ze^{-W} \operatorname{csch} Z - Re^{N_c} + e^{N_c} (\omega + z \coth Z)} \quad (38)$$

The next step is to represent ϕ as a function of ϵ_h .

This is done with some algebraic gymnastics as follows:

$$\phi = \frac{T_1 - t_2}{T_2 - t_1} = \frac{T_1 - t_2}{T_2 - T_1 + T_1 - t_1} = \frac{T_1 - t_2}{(T_1 - t_1) \left[\frac{T_1 - T_2}{T_1 - t_1} \right]}$$

or

$$\phi = \frac{T_1 - t_2}{(T_1 - t_1)(1 - \epsilon_h)}$$

Moreover

$$\phi = \frac{T_1 - t_2}{(T_1 - t_1)(1 - \epsilon_h)} = \frac{T_1 - t_1 + t_1 - t_2}{(T_1 - t_1)(1 - \epsilon_h)}$$

$$= \frac{(T_1 - t_1) \left[1 - \left(\frac{t_2 - t_1}{T_1 - t_1} \right) \left(\frac{T_1 - T_2}{T_1 - t_1} \right) \right]}{(T_1 - t_1)(1 - \epsilon_h)}$$

$$= \frac{1 - \left(\frac{T_1 - T_2}{T_1 - t_1} \right) \left(\frac{t_2 - t_1}{T_1 - T_2} \right)}{1 - \epsilon_h}$$

But $R_h = (t_2 - t_1)/(T_1 - T_2)$ so that

$$\phi = \frac{1 - \epsilon_h R_h}{1 - \epsilon_h}$$

or

$$\epsilon_h = \frac{\phi - 1}{\phi - R_h} \quad (39)$$

where ϕ is given by eq. (38)

The neatness of the form of eq. (39) is deceptive because, unfortunately, it cannot be used to determine a unique value for ϵ_h . The reason for this can be found in an inspection of eq. (38) which provides the value of ϕ which is used in eq. (39).

Notice in eq. (38) that Z , W and N_c are all functions of the product aL . On the other hand, w , z and R are functions of a only. Thus, it is impossible to vary a and L independently and still achieve a unique solution.

For example, suppose $a = 50 \text{ m}^2/\text{m}$ and $L = 5 \text{ m}$ so that $aL = 250$. A value of ϕ may be obtained from eq. (38) using these values. However, if $a = 100$ and $L = 2.5$ so that aL is still equal to 250, an entirely different value of ϕ is obtained because $a = 100$ rather than 50.

One should resist the temptation to multiply numerator and denominator of eq. (38) by L thereby creating a situation where only Z , W and N_c appear along with a new $R' = RL$. Such a procedure is doomed to failure because in dealing with an equation derived from n equations in $n+1$ unknowns, one cannot create the $n+1^{\text{th}}$ equation by multiplying one of the n equations by a constant. This makes the $n+1^{\text{th}}$ equation so obtained linearly dependent on one of the original n equations and the entire set becomes linearly dependent.

This section represents an attempt to obtain $\varepsilon = f(R, N_{tu})$ and the attempt has not been successful. It is now time to turn to the computer and this will be done in Section IV.

IV. NUMERICAL AND COMPUTER ANALYSIS

With a closed form solution for ϵ as a function of R and N_{tu} not attainable as indicated in Section III, it becomes apparent that an alternative method is needed to determine the effectiveness for the 1-3:2C and 1-3:2P heat exchangers. Kern and Kraus [Ref. 12: pp. 306-360] describe a computer code for a thermal analyzer. This code (program) makes use of node equations generated by finite differences and it employs a Cholesky LU decomposition scheme.

The Cholesky decomposition, as explained by Stewart [Ref. 13: pp. 134-144], is best used when decomposition in the presence of positive definite matrices is requested. This is the case at hand where one tries to solve numerically for the temperatures that lead to the effectiveness of the 1-3:2C and 1-3:2P heat exchangers.

A. THERMAL ANALYZER TVSSI

The computer program employed is Program TVSSI (Appendix A) which is an adaptation of the thermal analyzer program called TVSS2 and listed by Kern and Kraus [Ref. 12: pp. 306-360]. The adaptation consisted of changing the program so that it could perform the computations in the SI system of units and be receptive to the use of a specially created input file. Also it should be noted that TVSS2 was written

to be used in conjunction with the Honeywell H-1800 computer system. Therefore, it had to be modified to run on the Naval Postgraduate School's IBM 3033 AP system.

The program itself is a non-linear equation solver that determines the temperatures at a prescribed number of node-points or nodes from a set of node equations in almost any framework (i.e., network analysis, field plotting, or fluid flow distribution). It has certain features that make it primarily an equation solver for thermal analysis. These features include:

1. an ability to linearize radiation terms.
2. an ability to allow any of the coefficients in the node equations to vary with temperature.
3. an ability to provide constant heat input and heat input as a function of temperature at any node.
4. an ability to consider other modes of heat transfer that are non-linear such as boiling and natural convection.

As stated earlier, the program utilizes the Cholesky decomposition scheme and, because of the linearization of the radiation terms (a feature of the program that is used even though radiation does not appear in this $\epsilon - N_{tu}$ study), the program is iterative.

Cholesky's decomposition consists of finding a lower triangular matrix $[L]$ which is capable of reducing the original system of equations.

$$[K][T] = [Q] \quad (40)$$

or

$$[K][T] - [Q] = [0] \quad (41)$$

to the unit triangular form

$$[A][T] - [B] = [0] \quad (42)$$

so that the sought after elements of the column vector $[T]$ can be obtained by backward substitution.

Suppose, for example, that $[K]$ is 3×3 and assume that the system $[K][T] = [Q]$ has been reduced to the form $[A][T] - [B] = [0]$. In this event a premultiplication by $[L]$ will return the system to its original form, that is

$$[L]([A][T] - [B]) = [K][T] - [Q] = [0]$$

This implies that

$$[L][A] = [K] \quad (43)$$

and

$$[L][B] = [Q] \quad (44)$$

These equations allow the determination of $[L]$, $[A]$, and $[B]$ in a very simple manner and the matrices are uniquely determined because $[K]$ and $[Q]$ are known, or, at least are known after each iteration because the elements of $[K]$ are linearized. For a 3×3 system

$$\begin{array}{c} [K,Q] \end{array} \begin{bmatrix} k_{11} & k_{12} & k_{13} & q_1 \\ k_{21} & k_{22} & k_{23} & q_2 \\ k_{31} & k_{32} & k_{33} & q_3 \end{bmatrix} = \begin{array}{c} [L] \end{array} \begin{bmatrix} l_{11} & 0 & 0 \\ l_{21} & l_{22} & 0 \\ l_{31} & l_{32} & l_{33} \end{bmatrix} \begin{array}{c} [A,B] \end{array} \begin{bmatrix} 1 & a_{12} & a_{13} & b_1 \\ 0 & 1 & a_{23} & b_2 \\ 0 & 0 & 1 & b_3 \end{bmatrix}$$

one may obtain the following for the elements of [L], [A], and [B].

$$k_{i1} = (1)l_{i1} + (0)l_{i2} + (0)l_{i3} = l_{i1} \quad (45)$$

which shows that the first column of [L] is identical to the first column of [K].

$$k_{1j} = (l_{11})a_{1j} + (0)a_{2j} + (0)a_{3j} = l_{11}a_{1j} = k_{11}a_{1j} \quad (46)$$

which shows that the first row of [A] is equal to the first row of [K] divided by $[k_{11}]$ and then

$$k_{22} = l_{21}a_{12} + l_{22}(1) , \quad l_{22} = k_{22} - l_{21}a_{12}$$

$$k_{23} = l_{21}a_{13} + l_{22}a_{23} , \quad a_{23} = (k_{23} - l_{21}a_{13})/l_{22}$$

$$k_{32} = l_{31}a_{12} + l_{32}(1) , \quad l_{32} = k_{32} - l_{31}a_{12}$$

$$q_2 = l_{21}b_1 + l_{22}b_2 , \quad b_2 = (q_2 - l_{21}b_1)/l_{22}$$

In the foregoing manner the elements of [L], [A] and [B] are obtained successively in terms of previously determined elements in a progression that goes horizontally from l_{22} on. Thus the general relationship are seen to be

$$l_{ij} = k_{ij} - \sum_{r=1}^{j-1} l_{ir} k_{rj} \quad (47)$$

with

$$l_{i1} = k_{i1} \quad (48)$$

and

$$a_{ij} = \frac{1}{l_{ii}} [k_{ij} - \sum_{r=1}^{i-1} l_{ir} a_{rj}] \quad (49)$$

with

$$a_{ij} = \frac{k_{ij}}{k_{11}} \quad (50)$$

Moreover, it is observed that if $[K]$ is symmetrical which it must be in our coupled set of equations ($k_{ij} = k_{ji}$) then

$$l_{ij} = a_{ji} l_{ii} \quad (i, j = 1, 2, 3, \dots, n-1; i \neq j) \quad (51)$$

The modification for computation in the SI system was quick and simple. It involved changing a numeral in two places (460 to 273) and some format statements ($^{\circ}\text{F}$ to $^{\circ}\text{C}$ and Btu/hr to Watts).

The conversion of TVSS2 to TVSSI for running on the IBM 3033 AP system (which uses the FORTVS compiler) required

a modification to the Fortran program language used in TVSS2 in order to compile the FORTVS (basically international Fortran 77) system used on the IBM 3033.

B. INITIAL MODELING

Initially, the model was designed to find the temperatures that would allow computation of a single effectiveness value after a detailed set of capacity rate, coefficients and surface data were entered into the program. From the scope of the problem it was realized that multiple runs of the thermal analyzer program (TVSSI) would be needed. It therefore became necessary to develop a program that given C_h , C_c , U , A , T_1 , and t_1 , an input file would be created for use by the modified version of the thermal analyzer (TVSSI).

The first step taken was to develop a program to create an input file for TVSSI that would yield the effectiveness for a 1-4 heat exchanger which could be compared to the existing analytical solution for the effectiveness of a 1-4 exchanger. With this accomplished and confidence established, similar programs for the 1-3:2C and 1-3:2P exchangers could be developed. This program was called NTU14 (See Appendix B) and the following parameters were used for all runs.

1. 250 nodes were used.
2. The initial temperature for the computer to begin the iterative process was set at 200°C.

3. An eventual accuracy of .05 between the final and next to last iterations was used.
4. A radiation coefficient convergence factor of 0.66667 between iterations was used.
5. The maximum number of iterations that the computer was allowed to perform was set at 12.
6. A damping factor of .8 was set as an initial damping based on the number of non-linear terms in all of the node equations.

When the values of C_h , C_c , U , A , T_1 and t_1 are set, N_{tu} and R are then compiled and an input file for TVSSI was generated. In this file all node equations and internode conductance values were determined. This program determined and specified the nodes that interact with each other and the methods by which the interaction takes place such as conduction, forced convection, and fluid flow.

The program, NTU14, makes use of the fact that each term in a node equation shows three things. The first is the node that is coupled for heat flow with the node in question. The second is the method of heat flow between the nodes. In this case forced convection and fluid flow are used. Finally, the node equation shows the magnitude of the internode heat flow. Here all the pieces of information are collected and presented for use by TVSSI as an input file with all items in the proper format.

A comparison of the effectiveness for the 1-4 exchanger developed by the computer to that of using the closed form analytical solution for effectiveness developed by Kraus

and Kern [Ref. 8] as shown by equation (52)

$$\epsilon = \frac{2}{1 + R + \frac{1}{2}[1 + 4R^2]^{1/2} \coth\left(\frac{N_{tu}[1 + 4R^2]}{4}\right) + 4 \tanh \frac{N_{tu}}{4}} \quad (52)$$

was then undertaken. The results of this comparison showed that over the entire range of R from .01 to 1.0 for varying values of N_{tu} from 0 to 3.25 less than a 0.5% difference was ever realized. A small sample of these results are provided in Table 1. The conclusion to be drawn here, is that the methodology used to develop the computer program NTU14 for input to TVSSI for finding effectiveness was sound and could then be used in the development of the 1-3:2C and 1-3:2P exchanger methodology.

C. DEVELOPED MODELS FOR 1-3:2C AND 1-3:2P HEAT EXCHANGERS

The same technique used in developing the program NTU14 was used to generate computer programs NTU32C and NTU32P. These are listed in Appendices C and D. The departure for each of these programs from the NTU14 program is in the number of nodes; they are based on 200 node models as shown in Figures 4.1 and 4.2. An example of the output file generated from one of these programs is found at Appendix E. It is these values shown in Appendix E that are used by the thermal analyzer to determine the temperatures T_2 and t_2 for the specific set of given initial parameters C_h , C_c , R, A, T_1 , and t_1 .

TABLE 1
COMPUTER TO ANALYTICAL COMPARISON
FOR R = .5

N_{tu}	ANALYTICAL RESULTS	COMPUTER RESULTS	% DIFFERENCE
0.05	.0482	.0482	0.00
0.25	.2094	.2090	0.20
0.50	.3569	.3559	0.28
0.75	.4628	.4612	0.35
1.00	.5398	.5377	0.39
1.25	.5963	.5940	0.39
1.50	.6379	.6354	0.40
2.00	.6915	.6886	0.42
2.50	.7206	.7177	0.40
3.00	.7360	.7333	0.37
3.25	.7406	.7381	0.34

D. SCOPE OF COMPUTER ANALYSIS

At this point it is possible to let the computer solve for temperature values that yield a value for effectiveness based on a specific set of initial parameters. However, it must be realized that many computer runs are required to generate enough data to ensure confidence in the results which cover a wide range of capacity rate ratios and N_{tu} values.

To efficiently expedite the computer task, the Multiple Virtual System (MVS) with Job Entry Subsystem and Networking (JES3) was utilized. The MVS coupled with JES3 is more commonly referred to as batch processing. Based on trial and error, it was determined that in order to build a solid data base, eleven different values for effectiveness were needed to best represent a particular value of R . This was required over a range of R from $R = 0.1$ to 1.0 in increments of $.01$. In all, 200 curves for both the 1-3:2C and 1-3:2P exchangers were needed. This means that 2,200 unique values of effectiveness needed to be found, plus 100 values of effectiveness to be used for comparison with the 1-4 exchangers.

To complete this task, TVSSI was slightly modified in accordance with the appropriate guidelines of the job control language (JCL) needed to run on the batch processing system. These modifications are few and were needed only at the beginning and end of TVSSI. The modified version

of TVSSI has been called TVCOUNT with changes shown in Appendix F. It was TVCOUNT that was then used to activate TVSSI.

It also became necessary to modify the three input file programs NTU14, NTU32P and NTU32C such that they needed to be compiled only once. They were then loaded in a library file to be used when called by another program. New programs utilizing the batch system were written that could easily be loaded with the appropriate input data for a specific R value. These, which are referred to as "sister programs," were used to go from the library file to TVSSI and cause TVSSI to be executed eleven times under TVCOUNT covering the desired range of N_{tu} for a specific R value. The revised input files called NTU14C, NTU32CC, NTU32PC and their associated "sister execution programs," NTU14L, NTU32CL, NTU32PL, are found in Appendices G through L.

The overall system flow chart of how all of the foregoing is accomplished is found in Figures 4.3, 4.4 and 4.5. It is noted from these figures that TVSSI is referred to as TVSSIA through TVSSIV. These are the same programs as TVSSI but for bookkeeping purposes by the computer they are labeled A through V.

E. COMPUTER RESULTS

Upon completion of all data collection from the computer output, plots of effectiveness vs. N_{tu} for the whole range

of R were plotted and are shown in Appendices M and N. Thirty-three different plotting programs utilizing the "Display Integrated Software System and Plotting Language (DISSPLA)," were written to graph the data obtained. An example of one of these programs is provided in Appendix O.

Examination of the graphs in Figures 4.6, 4.7, and 4.8 shows that the 1-3:2C exchangers outperform the 1-3:2P, 1-2 and 1-4 exchangers. This is true in all cases, and, because of this, only a sample of the data was chosen to be shown in these figures. Furthermore, it is noted that at higher N_{tu} values, the effectiveness of the 1-3:2C exchanger is better than all of the others considered, while at higher capacity rate ratios, the effectiveness of 1-3:2C exchanger even begins to outperform the others at lower N_{tu} values. This increase in performance is easily understood because it has been proven by Kern [Ref. 1: pp. 139-137] and others that greater temperature differences result when process streams are in counterflow than parallel flow. Thus, when there is a combination of the two phenomena (counterflow and parallel flow) occurring, then it becomes apparent that the extra counterflow pass must increase the exchanger's overall performance.

As shown in the graphs in Appendices M and N, effectiveness increases as both R and N_{tu} increase. These curves can be used to give a graphical approximation of effectiveness

if that is all that is required. From the empirical data used to develop these curves, further investigation into the development of equations for these curves which may be used to determine an exact value of effectiveness when R and N_{tu} are known, is undertaken in Section V.

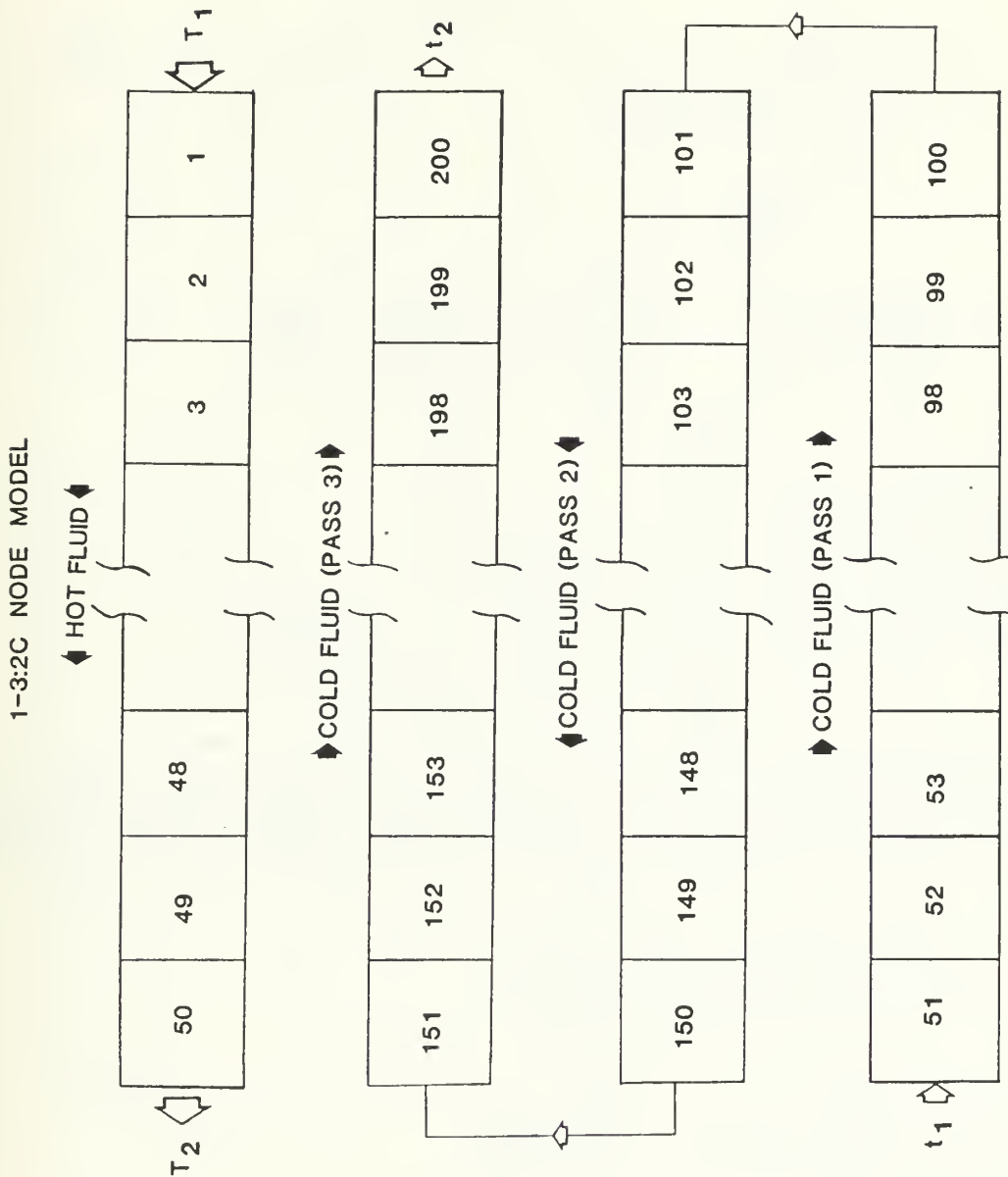


Figure 4.1 Nodal Arrangement for the 1-3:2C Exchanger

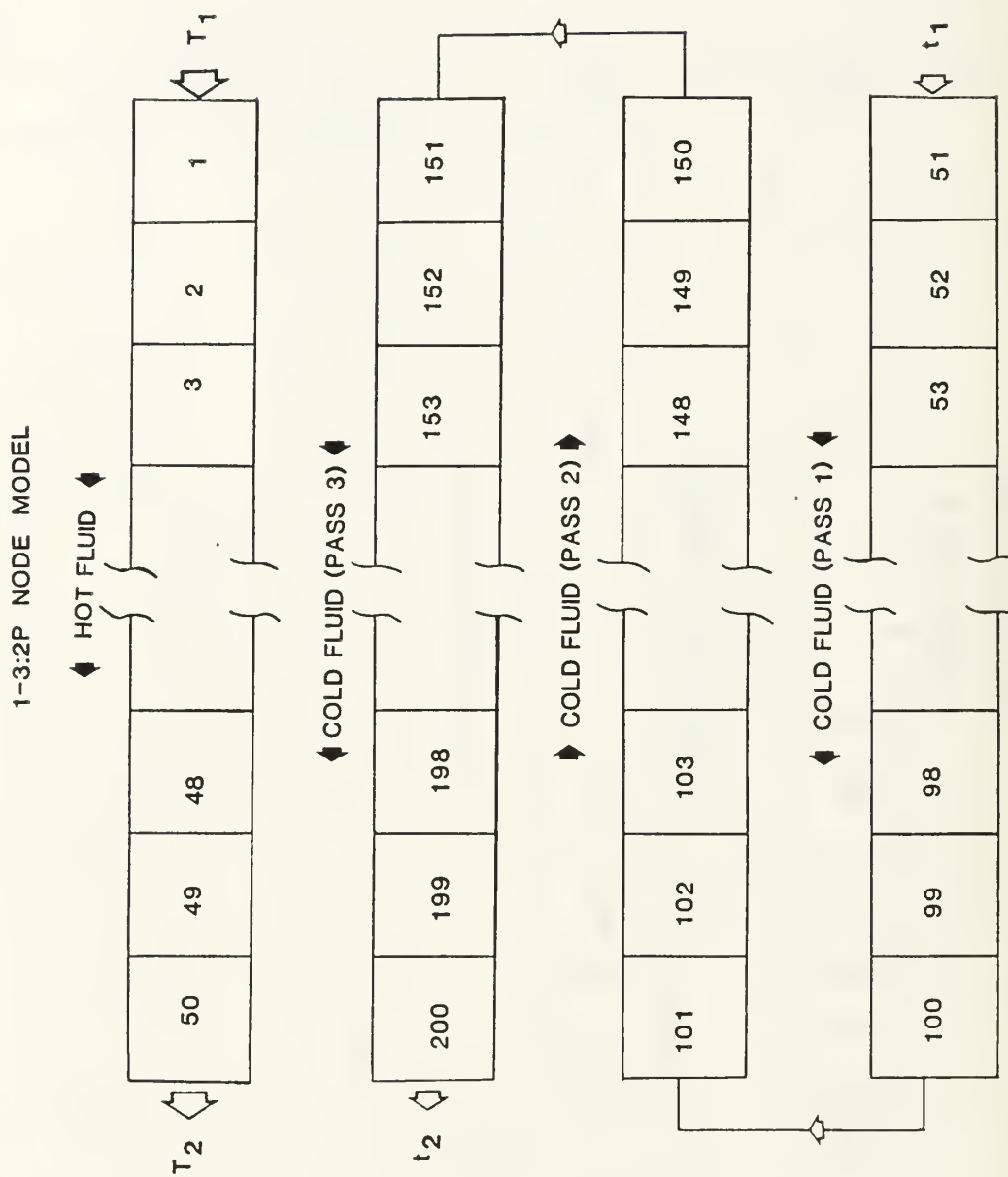


Figure 4.2 Nodal Arrangement for the 1-3:2P Exchanger

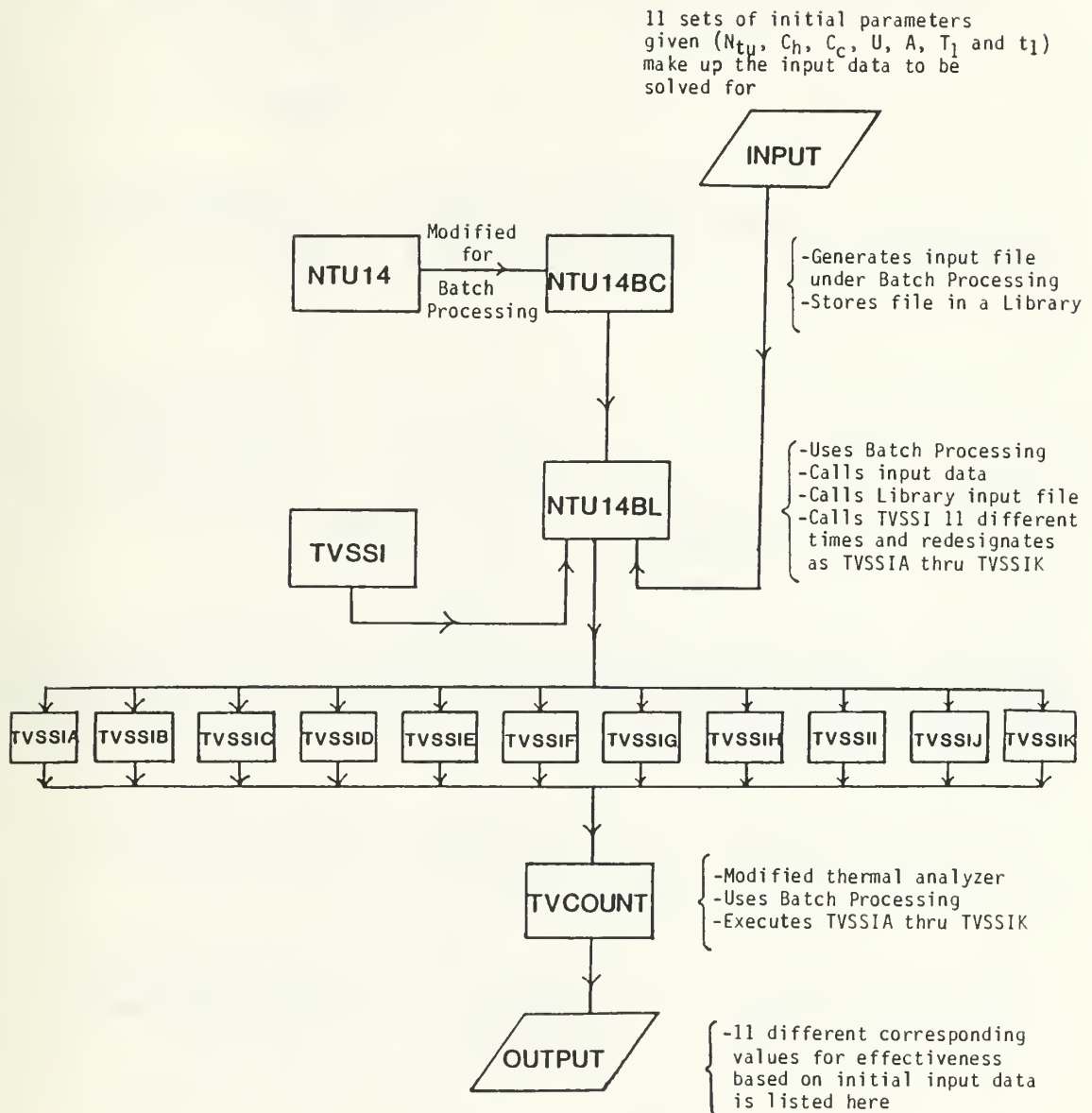


Figure 4.3 Computer Systems Flow Chart for 1-4 Exchanger Model

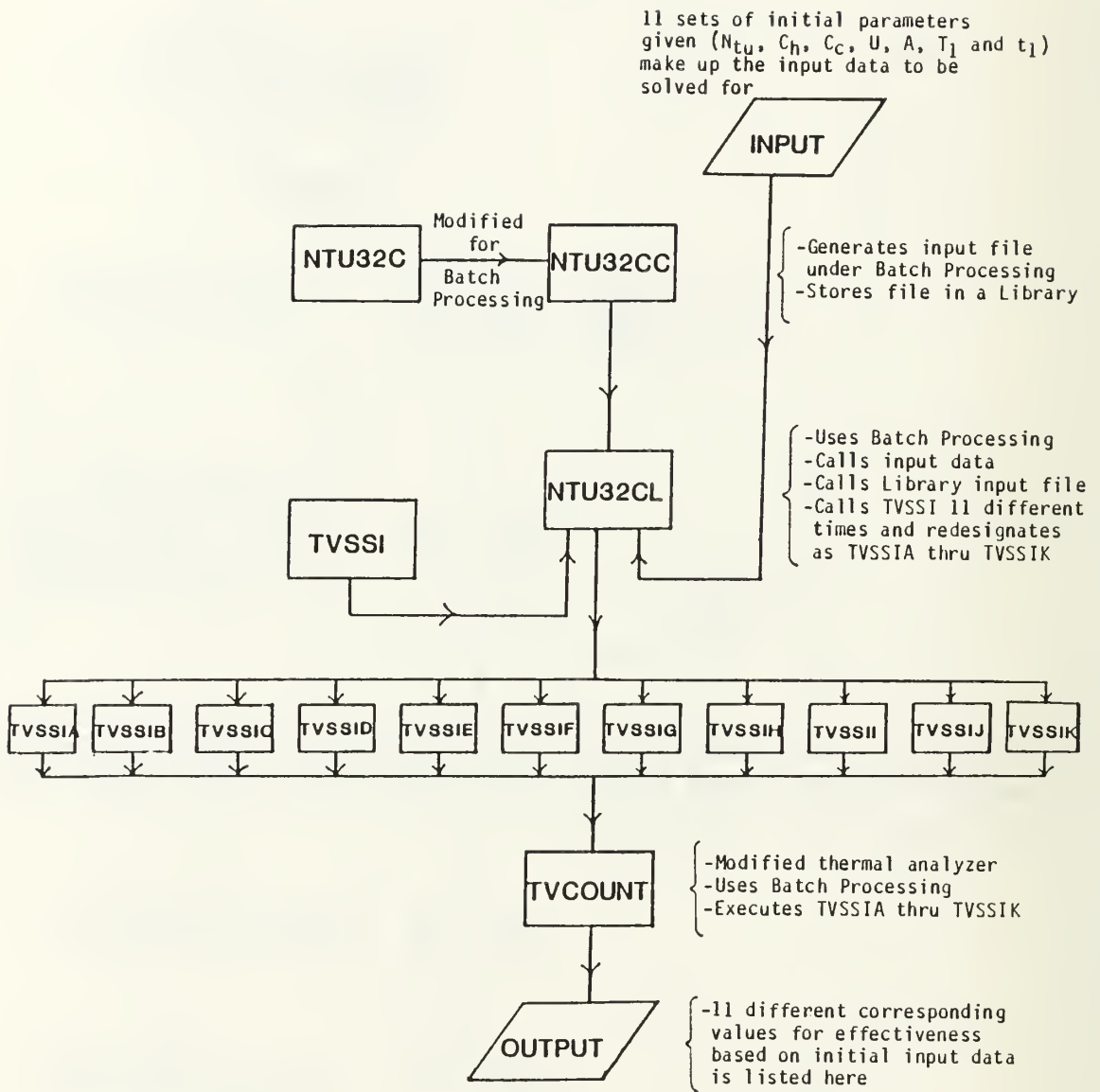


Figure 4.4 Computer Systems Flow Chart for 1-3:2C Exchanger Model

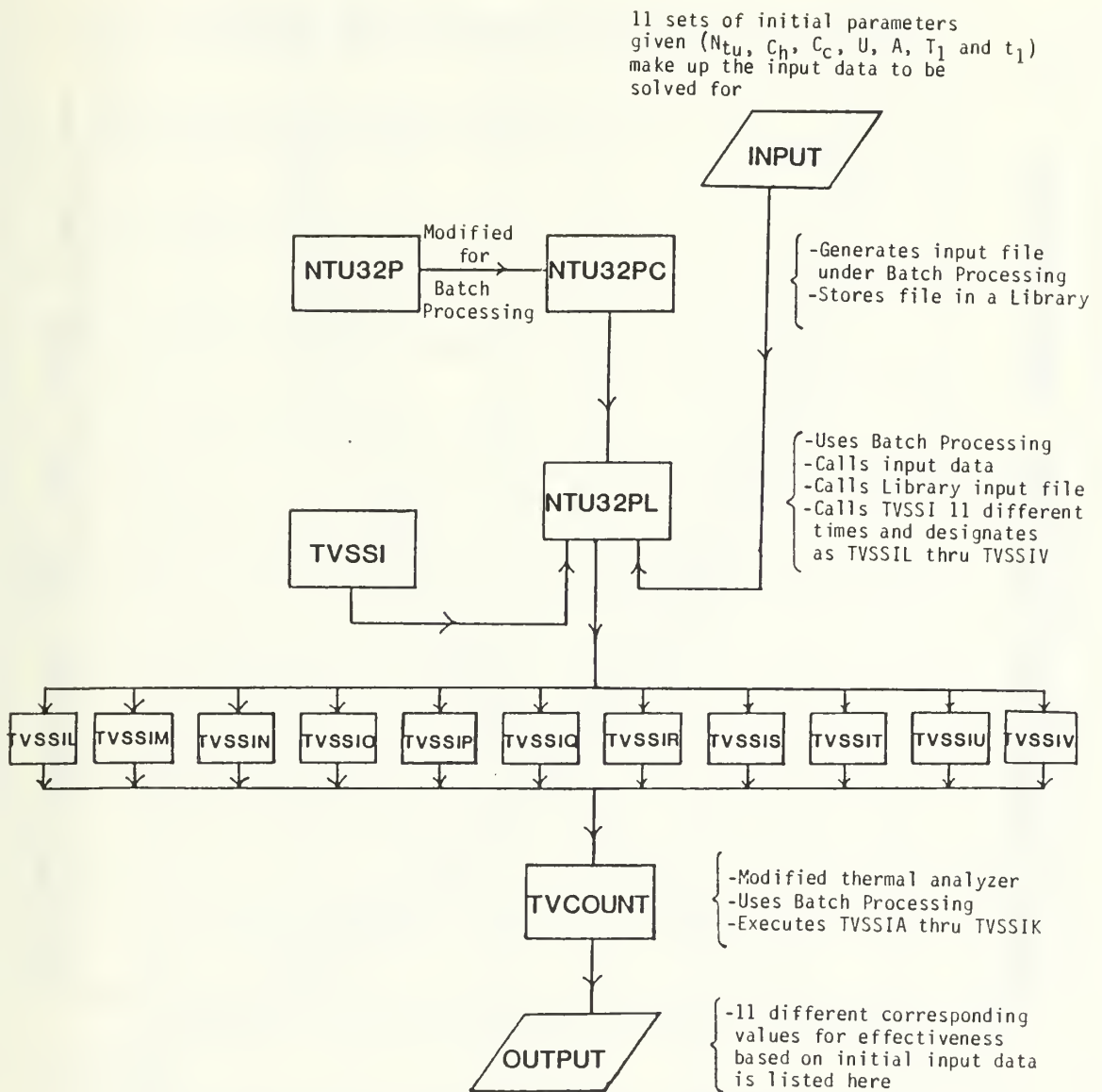


Figure 4.5 Computer Systems Flow Chart for 1-3:2P Exchanger Model

EFFECTIVENESS VS. NTU FOR $R=0.2$

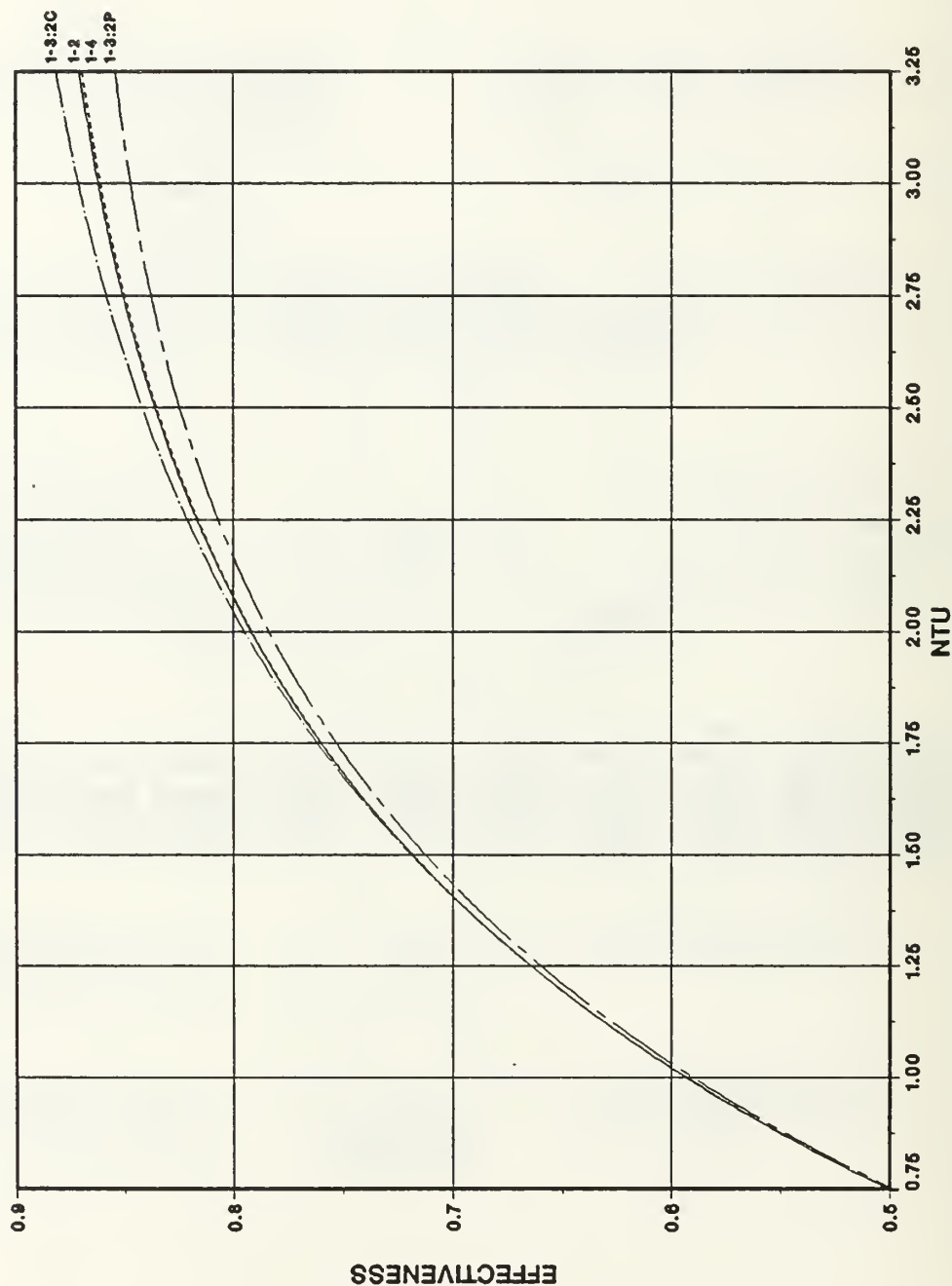


Figure 4.6 Comparison of Analytical (1-2 and 1-4) to Computer Results (1-3:2C and 1-3:2P) at $R = .2$

EFFECTIVENESS VS. NTU FOR $R=0.5$

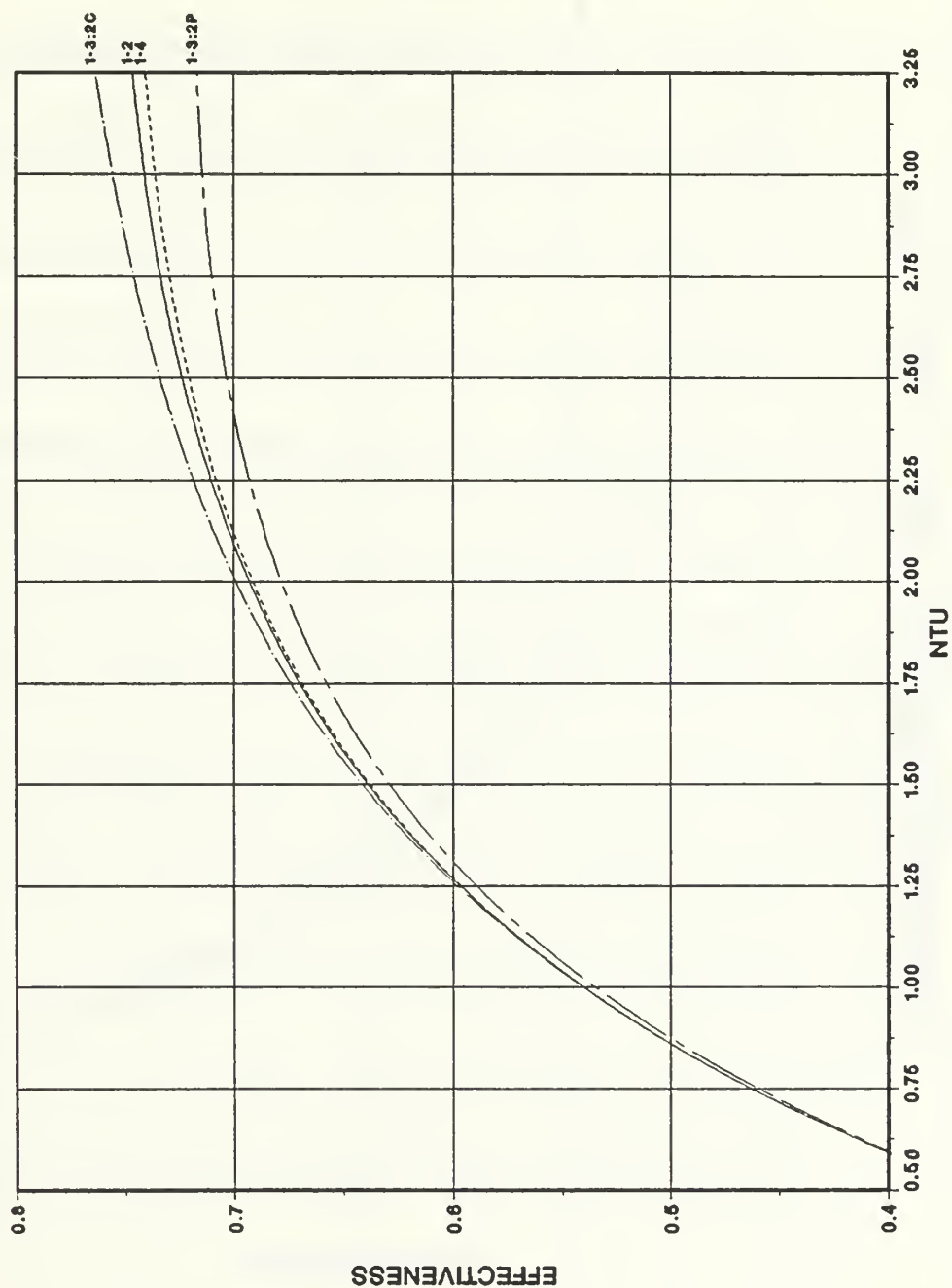


Figure 4.7 Comparison of Analytical (1-2 and 1-4) to Computer Results (1-3:2C and 1-3:2P) at $R = .5$

EFFECTIVENESS VS. NTU FOR $R=1.0$

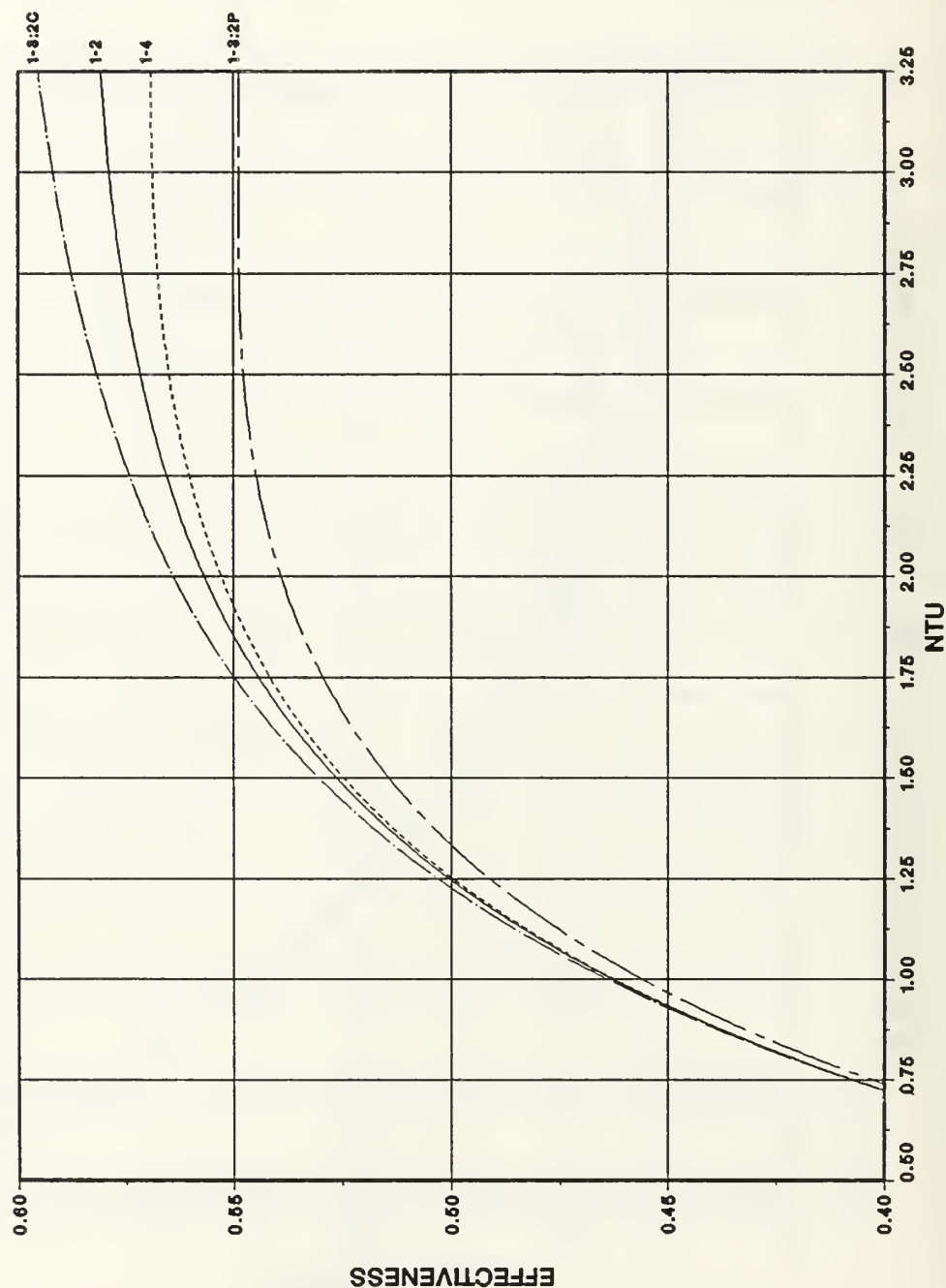


Figure 4.8 Comparison of Analytical (1-2 and 1-4) to Computer Results (1-3:2C and 1-3:2P) at $R = 1.0$

V. POLYNOMIAL REGRESSION

A. DEVELOPMENT OF POLYNOMIAL EQUATIONS

The empirical data obtained for the two 1-3 heat exchangers was designed to cover an extensive range of R values varying from 0.01 to 1.0 in increments of 0.01. As discussed earlier in Section IV, the data obtained at a specific value of R is the computer evaluated result of the effectiveness, for an associated N_{tu} value. With this accomplished, it then becomes possible to graph separate curves for each of the different R values as shown in Appendices M and N. Through a polynomial regression technique, as discussed in this section, it is also possible to develop implicit equations for the curves with $\epsilon = f(N_{tu}, R)$. It is also apparent from an inspection of the graphical representation of the empirical data in Appendices M and N, that the curves conform to a high degree polynomial. However, further analytical investigation is needed to ascertain the exact order of the polynomial terms. This investigation will not only lead to the order of the polynomial, but to the specific equation for each curve.

By use of polynomial regression, the least-squares method can be readily extended to best fit the data to the m^{th} -degree for the polynomial

$$y = A_0 + A_1x + A_2x^2 + \dots A_mx^m \quad (53)$$

with the error defined by

$$e_i = D_i - y_i = D_i - A_0 - A_1x - A_2x_i^2 - \dots - A_mx_i^m$$

where D_i represents the empirical data value corresponding to x_i , x_i being free of error.

The objective is to minimize the sum of the squares of the residuals, S_r ,

$$S_r = \sum_{i=1}^m e_i^2 = \sum (D_i - A_0 - A_1x_1 - A_2x_2^2 + \dots - A_mx^m)^2 \quad (54)$$

Because at a minimum, the partial derivatives $\partial S_r / \partial A_0$, $\partial S_r / \partial A_1 \dots \partial S_r / \partial A_m$ vanish, after taking the derivative of S_r with respect to each of the coefficients of the polynomial, it can be seen that

$$\frac{\partial S_r}{\partial A_0} = 0 = -2 \sum (D_i - A_0 - A_1x_i - A_2x_i^2 - \dots - A_mx_i^m)$$

$$\frac{\partial S_r}{\partial A_1} = 0 = -2 \sum x_i (D_i - A_0 - A_1x_i - A_2x_i^2 - \dots - A_mx_i^m)$$

$$\frac{\partial S_r}{\partial A_2} = 0 = -2 \sum x_i^2 (D_i - A_0 - A_1x_i - A_2x_i^2 - \dots - A_mx_i^m)$$

$$\vdots$$

$$\frac{\partial S_r}{\partial A_m} = 0 = -2 \sum x_i^m (D_i - A_0 - A_1x_i - A_2x_i^2 - \dots - A_mx_i^m)$$

Then by dividing by -2 and rearranging we obtain

$$A_0M + A_1 \sum x_i + A_1 x_i^2 + \dots + A_m \sum x_i^m = \sum D_i$$

$$A_0 \sum x_i + A_1 \sum x_i^2 + A_2 \sum x_i^3 + \dots + A_m \sum x_i^{m+1} = \sum x_i D_i$$

$$A_0 \sum x_i^2 + A_1 \sum x_i^3 + A_2 \sum x_i^4 + \dots + A_m \sum x_i^{m+2} = \sum x_i^2 D_i$$

$$\begin{array}{ccccccc} \cdot & & \cdot & & \cdot & & \cdot \\ \cdot & & \cdot & & \cdot & & \cdot \\ \cdot & & \cdot & & \cdot & & \cdot \end{array}$$

$$A_0 \sum x_i^m + A_1 \sum x_i^{m+1} + A_2 \sum x_i^{m+2} + \dots + A_m \sum x_i^{2m} = \sum x_i^m D_i$$

where all summations are from $i=1$ through n . All of the foregoing $m+1$ equations are linear and have $m+1$ unknowns: $A_0, A_1, A_2, \dots, A_m$. The coefficients of the unknowns can be calculated directly from the observed data. Thus, the problem of determining a least-squares polynomial of degree m is equivalent to solving a system of $m+1$ simultaneous linear equations. Putting the equations in matrix form yields

$$\begin{bmatrix} N & \sum x_i & \sum x_i^2 & \sum x_i^3 & \dots & \sum x_i^m \\ \sum x_i & \sum x_i^2 & \sum x_i^3 & \sum x_i^4 & \dots & \sum x_i^{m+1} \\ \sum x_i^2 & \sum x_i^3 & \sum x_i^4 & \sum x_i^5 & \dots & \sum x_i^{m+2} \\ \cdot & \cdot & \cdot & \cdot & \dots & \cdot \\ \cdot & \cdot & \cdot & \cdot & \dots & \cdot \\ \cdot & \cdot & \cdot & \cdot & \dots & \cdot \\ \sum x_i^m & \sum x_i^{m+1} & \sum x_i^{m+2} & \sum x_i^{m+3} & \dots & \sum x_i^{2m} \end{bmatrix} [A] = \begin{bmatrix} \sum D_i \\ \sum x_i D_i \\ \sum x_i^2 D_i \\ \cdot \\ \cdot \\ \cdot \\ \sum x_i^m D_i \end{bmatrix}$$

[Ref. 15: pp. 302-309 and Ref. 16: 468-474].

From this point on, one finds that it is best to use a computer to assist in solving the simultaneous equations and this will also help alleviate any ill-conditioning that may otherwise occur. An existing "curvefit" program available through NON-IMSL [Ref. 16] and found in Appendix P was used although some modifications were made to the original program to best accommodate the goals of this work.

To determine the order of polynomial that should eventually be used, one increases the degree of the approximating polynomial as long as there is a statistically significant decrease in the variance σ^2 , which is computed by

$$\sigma^2 = \frac{\sum e_i^2}{N - m - 1} \quad (55)$$

In otherwords, the selection of the optimum degree polynomial is contingent upon a decreasing variance and once the variance begins to increase, the degree of the polynomial becomes too high. For all cases, it was found that the $\epsilon - N_{tu}$ developed curves are of the 5th order.

As shown in Figures 5.1 and 5.2 the computed values of effectiveness vs. N_{tu} for $R = 0.1, 0.5$ and 1.0 for both flow arrangements, (1-3:2P) and (1-3:2C), have been graphed and fitted by a 5th degree polynomial. Because all computed values for effectiveness follow a predictable trend, only a sample of the data covering the whole range of

values of R have been shown. It is clear that the graphic interpretation strongly backs what is known analytically from the polynomial regression technique. Where the relationship for $\epsilon = f(N_{tu}, R)$ is found explicitly from

$$\epsilon = A_5 N_{tu}^5 + A_4 N_{tu}^4 + A_3 N_{tu}^3 + A_2 N_{tu}^2 + A_1 N_{tu} + A_0 \quad (56)$$

while the corresponding coefficients A_5, A_4, A_3, A_2, A_1 , and A_0 relating to a specific value of R are found in Tables 2 and 3 for the (1-3:2P) and (1-3:2C) configurations. An example of how to use this equation in a heat exchanger problem now follows.

B. NUMERICAL EXAMPLE

Consider a heat exchanger containing 400 m^2 of ($A = 400 \text{ m}^2$) of surface and operating with an overall heat transfer coefficient of $80 \text{ W/m}^2\text{°C}$. Cold fluid at a capacity rate of $10,000 \text{ W/°C}$ enters the exchanger at 60°C . Hot fluid at a capacity rate of $20,000 \text{ W/°C}$ enters the exchanger at 200°C .

1. Find

The effectiveness (ϵ) and compute the hot and cold fluid outlet temperatures for the (1-3:2C) shell tube pass arrangement.

2. Assumptions

- 1) Negligible heat loss to surroundings and kinetic and potential energy changes.

- 2) Constant thermal and fluid properties for both fluids.

3. Analysis

Here $C_c = 10,000 \text{ W/}^\circ\text{C}$ and $C_h = 20,000 \text{ W/}^\circ\text{C}$ this makes $R = C_{\min}/C_{\max} = C_c/C_h = (T_1 - T_2)/(t_2 - t_1)$

$$10,000/20,000 = 0.5.$$

$$\text{and } N_{tu} = UA/C_c$$

$$= 80 (400)/(10,000) = 3.2$$

First, go to Table 2 (page 81) for the (1-3:2C) arrangement with $R = 0.5$ and find the coefficients

$$A_0 = 0.1294 \times 10^{-2}$$

$$A_1 = 0.98120$$

$$A_2 = -0.66161$$

$$A_3 = 0.27933$$

$$A_4 = -0.66456 \times 10^{-1}$$

$$A_5 = 0.66069 \times 10^{-2}$$

Then apply equation (56) for $N_{tu} = 3.2$

$$\epsilon = A_5 N_{tu}^5 + A_4 N_{tu}^4 + A_3 N_{tu}^3 + A_2 N_{tu}^2 + A_1 N_{tu} + A_0 \quad (56)$$

$$\epsilon = 0.769$$

Because $C_c < C_h$

$$\epsilon = \frac{t_2 - t_1}{T_1 - t_1}$$

and with $T_1 - t_1 = 200 - 60 = 140^\circ\text{C}$

$$\begin{aligned} t_2 - t_1 &= \epsilon(T_1 - t_1) \\ &= 0.769 (140) \\ &= 107.7^\circ\text{C} \end{aligned}$$

Finally, the outlet cold fluid temperature t_2 is

$$\begin{aligned} t_2 &= 107.7 + t_1 \\ &= 107.7 + 60 \\ &= 167.7^\circ\text{C} \end{aligned}$$

and the fluid temperature, T_2 is easily found

$$R = \frac{T_1 - T_2}{t_2 - t_1} = 0.5$$

$$\begin{aligned} T_2 &= T_1 - 0.5 (t_2 - t_1) \\ &= 200 - 0.5 (t_2 - t_1) \\ &= 146.1^\circ\text{C} \end{aligned}$$

4. Observations

The primary observation made here is that by using the 5th order polynomial equation (56) with the appropriate coefficients found in Table 2 or 3, an accurate value for

effectiveness can be found thus allowing one to solve for many more unknown values or parameters of the heat exchanger (i.e., hot and cold outlet temperatures).

The other observation that is to be made is that when comparing the value for effectiveness computed here against the value for a 1-2 or 1-4 exchanger (0.745 and 0.740 respectively) under the same conditions, one finds that there is a significant difference in exchanger performance as a function of odd or even tube passes and that the 1-3:2C arrangement has a higher effectiveness than either the 1-2 or 1-4 arrangement. From inspection of the curves for the 1-3:2P exchanger at Figure N-1 or N-6 with $R = 0.5$ and $N_{tu} = 3.2$ an approximate value of $\epsilon = .715$ is obtained. It is clear that this is also less than that of 1-3:2C arrangement. Therefore, it is evident that the 1-3:2C exchanger out-performs not only the 1-2 and 1-4 arrangement but also its counterpart the 1-3:2P exchanger by 3.1%, 3.8% and 7.0% respectfully.

EFFECTIVENESS VS. NTU **2 OUT OF 3 PASSES IN COUNTER FLOW** **DATA POINTS FIT BY 6TH ORDER POLYNOMIAL**

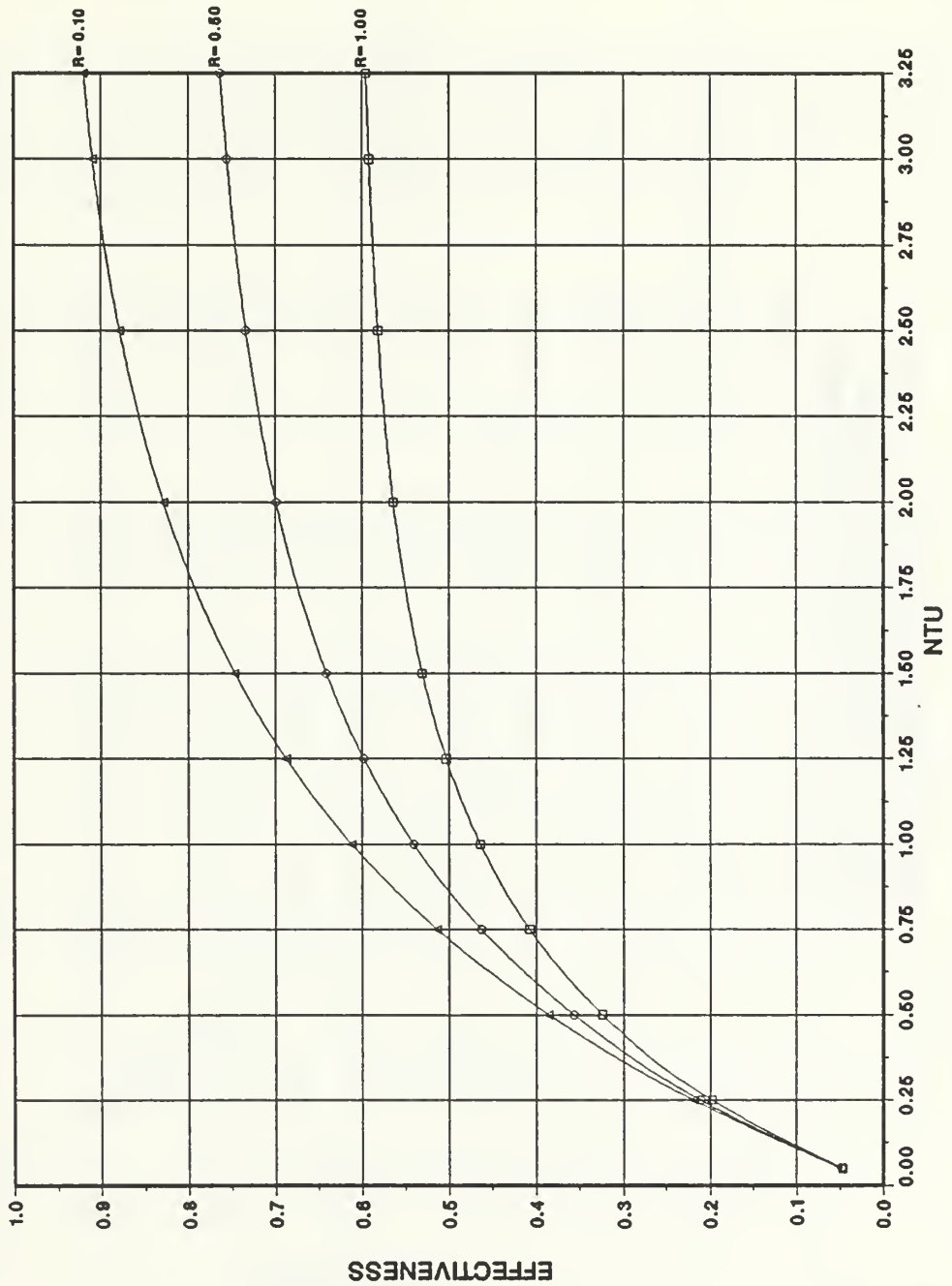


Figure 5.1 1-3:2C Data Fit by a 5th Order Polynomial

EFFECTIVENESS VS. NTU 2 OUT OF 3 PASSES IN PARALLEL FLOW DATA POINTS FIT BY 5TH ORDER POLYNOMIAL

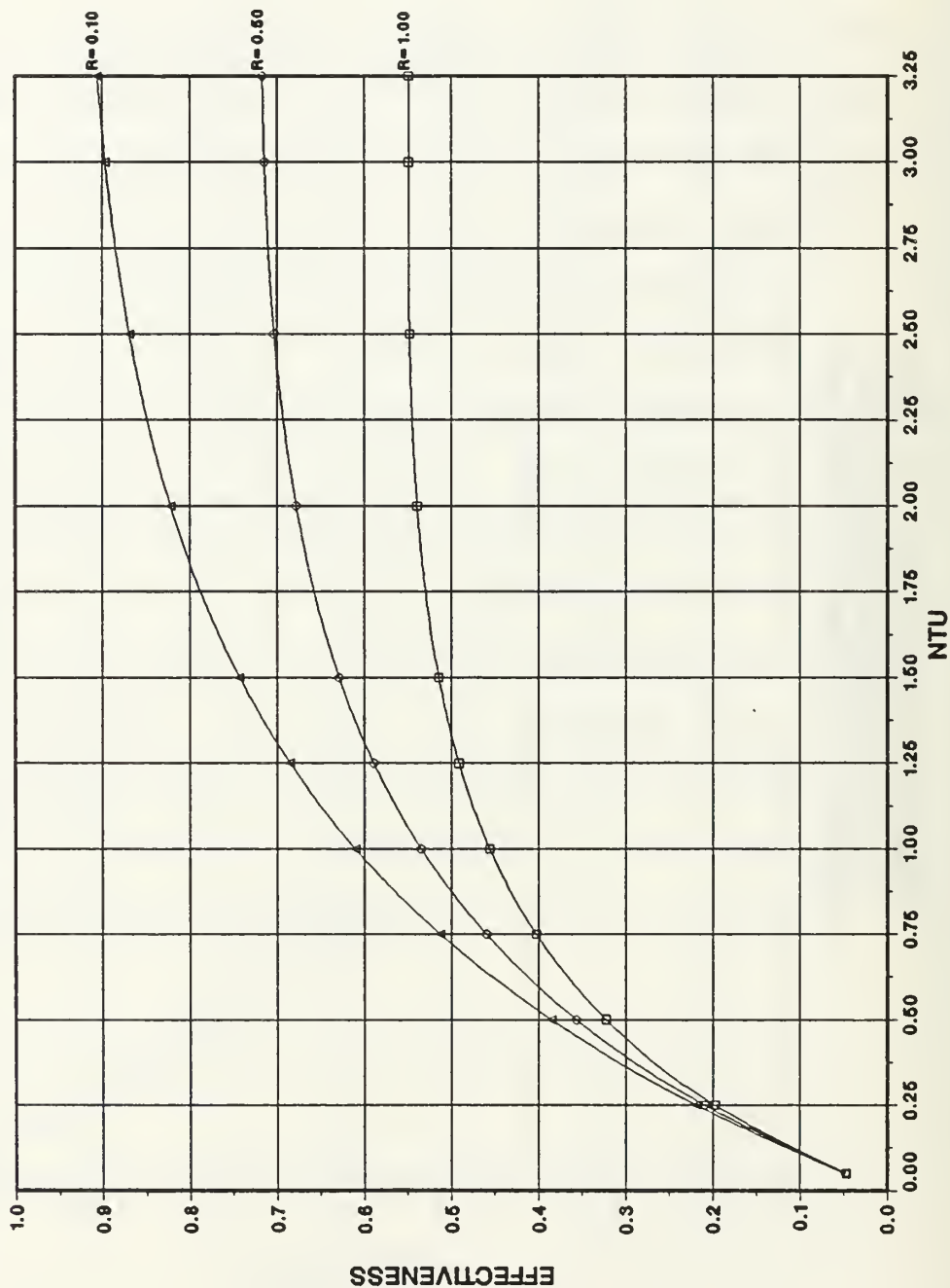


Figure 5.2 1-3:2P Data Fit by a 5th Order Polynomial

TABLE 2
1-3:2C COEFFICIENTS

R	$A_0 \times 10^3$	A_1	A_2	A_3	$A_4 \times 10^1$	$A_5 \times 10^2$
.01	-1.54650	1.00630	-0.51115	0.16418	-0.31787	0.27562
.02	1.09620	0.98977	-0.48530	0.14498	-0.25435	0.19915
.03	0.23928	0.99515	-0.49950	0.15565	-0.28857	0.23943
.04	-0.23948	0.99772	-0.50794	0.16165	-0.30646	0.25908
.05	0.70811	0.99188	-0.50226	0.15792	-0.29488	0.24608
.06	0.36469	0.99329	-0.50845	0.16207	-0.30594	0.25657
.07	0.17636	0.99546	-0.51698	0.16867	-0.32725	0.28161
.08	0.62843	0.99167	-0.51309	0.16524	-0.31420	0.26475
.09	0.41140	0.99354	-0.52158	0.17208	-0.33695	0.29217
.10	0.47085	0.99198	-0.52163	0.17131	-0.33137	0.28264
.11	0.68979	0.99116	-0.52589	0.17555	-0.34744	0.30429
.12	0.53544	0.99173	-0.53101	0.17938	-0.35920	0.31765
.13	0.38892	0.99173	-0.53462	0.18182	-0.36561	0.32373
.14	0.76975	0.98852	-0.53226	0.17971	-0.35696	0.31186
.15	0.60634	0.98885	-0.53636	0.18229	-0.36288	0.31623
.16	0.40649	0.98999	-0.54245	0.18673	-0.37606	0.33043
.17	0.73099	0.98713	-0.54081	0.18557	-0.37211	0.32587
.18	0.46417	0.98875	-0.54820	0.19109	-0.38883	0.34412
.19	0.90075	0.98061	-0.52634	0.16874	-0.30036	0.22473

TABLE 2 (cont'd)
1-3:2C COEFFICIENTS

R	$A_0 \times 10^3$	A_1	A_2	A_3	$A_4 \times 10^1$	$A_5 \times 10^2$
.20	0.71140	0.98703	-0.55346	0.19530	-0.40158	0.35808
.21	0.64893	0.98700	-0.5575	0.19879	-0.41317	0.37222
.22	0.56702	0.98762	-0.56291	0.20258	-0.42439	0.38422
.23	0.71515	0.98611	-0.56423	0.20381	-0.42850	0.38931
.24	0.61725	0.98692	-0.56969	0.20786	-0.44087	0.40315
.25	0.57119	0.98653	-0.57241	0.20960	-0.44493	0.40637
.26	0.79180	0.98547	-0.57511	0.21210	-0.45381	0.41785
.27	0.69607	0.98591	-0.58041	0.21654	-0.46901	0.43663
.28	0.62722	0.98553	-0.58350	0.21893	-0.47655	0.44549
.29	0.79437	0.98544	-0.58911	0.22410	-0.49504	0.46888
.30	0.67158	0.98625	-0.59584	0.23115	-0.52608	0.51644
.31	0.74865	0.98380	-0.59141	0.22464	-0.49281	0.46289
.32	0.92219	0.98226	-0.59256	0.22572	-0.49644	0.46752
.33	0.82224	0.98264	-0.59730	0.22942	-0.50820	0.48114
.34	0.88180	0.98243	-0.60118	0.23262	-0.51887	0.49414
.35	0.10262	0.98083	-0.60162	0.23267	-0.51751	0.49105
.36	0.99038	0.98036	-0.60424	0.23460	-0.52330	0.49765
.37	0.91970	0.98036	-0.60770	0.23702	-0.53023	0.50506
.38	1.08830	0.97884	-0.60875	0.23792	-0.53284	0.50798
.39	1.11470	0.97855	-0.61207	0.24047	-0.54058	0.51644

TABLE 2 (cont'd)
1-3:2C COEFFICIENTS

R	$A_0 \times 10^3$	A_1	A_2	A_3	$A_4 \times 10^1$	$A_5 \times 10^2$
.40	1.17740	0.97771	-0.61372	0.24125	-0.54130	0.51566
.41	1.21820	0.97688	-0.61606	0.24330	-0.54828	0.52441
.42	1.13560	0.97705	-0.61993	0.24606	-0.55618	0.53262
.43	1.17390	0.97657	-0.62278	0.24826	-0.56290	0.54017
.44	1.25770	0.97508	-0.62296	0.24798	-0.56028	0.53543
.45	1.30410	0.97449	-0.62533	0.24946	-0.56329	0.53694
.46	1.20250	0.97496	-0.63022	0.25345	-0.57673	0.55343
.47	1.39770	0.97310	-0.63045	0.25368	-0.57704	0.55347
.48	1.45510	0.97221	-0.63176	0.25421	-0.57681	0.55130
.49	2.63160	0.94641	-0.77159	0.35867	-0.89176	0.90142
.50	1.29400	0.98102	-0.66161	0.27938	-0.66456	0.66069
.51	1.46920	0.97076	-0.63972	0.26012	-0.59397	0.56948
.52	1.50140	0.97079	-0.64398	0.26376	-0.60667	0.58553
.53	1.54710	0.96986	-0.64538	0.26447	-0.60718	0.58416
.54	1.56460	0.96971	-0.64922	0.26778	-0.61866	0.59853
.55	1.46430	0.97013	-0.65396	0.27164	-0.63151	0.61405
.56	1.65860	0.96803	-0.65281	0.27025	-0.62482	0.60403
.57	1.68550	0.96775	-0.65632	0.27325	-0.63507	0.61674
.58	1.63300	0.96751	-0.65932	0.27553	-0.64200	0.62444

TABLE 2 (cont'd)
1-3:2C COEFFICIENTS

R	$A_0 \times 10^3$	A_1	A_2	A_3	$A_4 \times 10^1$	$A_5 \times 10^2$
.59	1.77010	0.96636	-0.66068	0.27651	-0.64435	0.62630
.60	1.85570	0.96466	-0.66124	0.27649	-0.64120	0.61866
.61	1.76480	0.96543	-0.66567	0.28014	-0.65464	0.63700
.62	1.74620	0.96535	-0.66936	0.28319	-0.66476	0.64910
.63	1.80880	0.96455	-0.67135	0.28478	-0.66975	0.65496
.64	1.72290	0.96471	-0.67523	0.28786	-0.67963	0.66649
.65	1.85600	0.96393	-0.67750	0.28960	-0.68455	0.67144
.66	1.81240	0.96311	-0.67878	0.29033	-0.68584	0.67199
.67	1.82510	0.96293	-0.68231	0.29330	-0.69586	0.68424
.68	1.87880	0.96231	-0.68466	0.29518	-0.70174	0.69110
.69	1.88370	0.96227	-0.68863	0.29860	-0.71344	0.70539
.70	1.96850	0.96109	-0.68955	0.29922	-0.71473	0.70618
.71	1.98700	0.96047	-0.69161	0.30065	-0.71834	0.70940
.72	2.00210	0.96018	-0.69436	0.30265	-0.72405	0.71533
.73	1.95690	0.95987	-0.69723	0.30501	-0.73180	0.72461
.74	2.08210	0.95882	-0.69884	0.30640	-0.73620	0.72971
.75	2.00140	0.95886	-0.70230	0.30908	-0.74462	0.73945
.76	2.07320	0.95796	-0.70372	0.31004	-0.74680	0.74106
.77	2.14030	0.95700	-0.70520	0.31115	-0.74972	0.74373
.78	2.10090	0.95754	-0.71036	0.31567	-0.76577	0.76409

TABLE 2 (cont'd)
1-3:2C COEFFICIENTS

R	$A_0 \times 10^3$	A_1	A_2	A_3	$A_4 \times 10^1$	$A_5 \times 10^2$
.79	2.17470	0.95647	-0.71149	0.31638	-0.76691	0.76409
.80	2.22410	0.95612	-0.71500	0.31955	-0.77811	0.77833
.81	2.29050	0.95454	-0.71442	0.31881	-0.77439	0.77261
.82	2.17700	0.95505	-0.71882	0.32224	-0.78513	0.78474
.83	2.36540	0.95352	-0.71902	0.32235	-0.78494	0.78416
.84	2.25330	0.95366	-0.72313	0.32610	-0.79853	0.80160
.85	2.31490	0.95324	-0.72564	0.32788	-0.80318	0.80576
.86	2.33970	0.95252	-0.72764	0.32960	-0.80894	0.81289
.87	2.42210	0.95135	-0.72849	0.33023	-0.81036	0.81397
.88	2.46190	0.95078	-0.73069	0.33197	-0.81554	0.81943
.89	2.50950	0.94972	-0.73156	0.33251	-0.81640	0.81960
.90	2.55370	0.94902	-0.73371	0.33440	-0.82268	0.82712
.91	2.48350	0.94906	-0.73726	0.33739	-0.83276	0.83937
.92	2.62780	0.94803	-0.73861	0.33847	-0.83576	0.84233
.93	2.53660	0.94826	-0.74226	0.34133	-0.84485	0.85293
.94	2.62050	0.94709	-0.74336	0.34240	-0.84835	0.85688
.95	2.63490	0.94638	-0.74494	0.34352	-0.85120	0.85945
.96	2.70740	0.94547	-0.74656	0.34495	-0.85586	0.86503
.97	2.72560	0.94513	-0.74924	0.34722	-0.86335	0.87396

TABLE 2 (cont'd)
1-3:2C COEFFICIENTS

R	$A_0 \times 10^3$	A_1	A_2	A_3	$A_4 \times 10^1$	$A_5 \times 10^2$
.98	2.75280	0.94473	-0.75178	0.34931	-0.86995	0.88147
.99	2.79380	0.94417	-0.75421	0.35148	-0.87737	0.89055
1.0	2.77220	0.94336	-0.75536	0.35222	-0.87876	0.89109

TABLE 3
1-3:2P COEFFICIENTS

R	$A_0 \times 10^3$	A_1	A_2	A_3	$A_4 \times 10^1$	$A_5 \times 10^2$
.01	-1.53750	1.00620	-0.51077	0.16346	-0.31456	0.27066
.02	1.11580	0.98955	-0.48504	0.14443	-0.25245	0.19708
.03	0.26058	0.99459	-0.49839	0.15419	-0.28333	0.23299
.04	-0.14339	0.99665	-0.50600	0.15936	-0.29827	0.24901
.05	0.71311	0.99151	-0.50132	0.15581	-0.28564	0.23286
.06	-0.76150	0.99957	-0.51965	0.16930	-0.32915	0.28450
.07	0.00791	0.99690	-0.52063	0.17043	-0.33265	0.28805
.08	0.53649	0.99321	-0.51784	0.16820	-0.32501	0.27915
.09	0.45711	0.99282	-0.52061	0.16963	-0.32731	0.27957
.10	0.32341	0.99298	-0.52472	0.17231	-0.33459	0.28716
.11	0.63371	0.99174	-0.52796	0.17532	-0.34560	0.30175
.12	0.44811	0.99423	-0.53763	0.18264	-0.36872	0.32827
.13	0.40379	0.99141	-0.53466	0.17935	-0.35466	0.30842
.14	0.80291	0.98808	-0.53222	0.17711	-0.34561	0.29604
.15	0.55870	0.98956	-0.53929	0.18226	-0.36119	0.31312
.16	0.39008	0.99034	-0.54496	0.18651	-0.37453	0.32851
.17	0.61833	0.98887	-0.54674	0.18791	-0.37882	0.33344
.18	0.37408	0.99011	-0.55323	0.19272	-0.39372	0.35028
.19	0.44322	0.98934	-0.55579	0.19446	-0.39841	0.35493

TABLE 3 (cont'd)
1-3:2P COEFFICIENTS

R	$A_0 \times 10^3$	A_1	A_2	A_3	$A_4 \times 10^1$	$A_5 \times 10^2$
.20	0.65879	0.98800	-0.55782	0.19608	-0.40326	0.36012
.21	0.62161	0.98815	-0.56240	0.19955	-0.41423	0.37300
.22	0.52051	0.98852	-0.56700	0.20282	-0.42390	0.38353
.23	0.70119	0.98663	-0.56742	0.20307	-0.42417	0.38350
.24	0.55381	0.98769	-0.57404	0.20845	-0.44276	0.40697
.25	0.50155	0.98755	-0.57772	0.21100	-0.44987	0.41422
.26	0.75200	0.98606	-0.57918	0.21217	-0.45355	0.41867
.27	0.67777	0.98627	-0.58389	0.21587	-0.46579	0.43366
.28	0.64963	0.98566	-0.58598	0.21689	-0.46711	0.43334
.29	0.89133	0.98422	-0.58768	0.21821	-0.47081	0.43704
.30	0.83692	0.98406	-0.59124	0.22081	-0.47884	0.44648
.31	0.72206	0.98469	-0.59633	0.22452	-0.49011	0.45909
.32	0.88562	0.98325	-0.59765	0.22550	-0.49292	0.46229
.33	0.81793	0.98323	-0.60125	0.22803	-0.50028	0.47027
.34	0.93507	0.98177	-0.60195	0.22811	-0.49868	0.46646
.35	1.02360	0.98140	-0.60574	0.23118	-0.50876	0.47864
.36	1.00020	0.98080	-0.60808	0.23263	-0.51221	0.48161
.37	0.93995	0.98064	-0.61149	0.23506	-0.51930	0.48934
.38	1.03810	0.98003	-0.61416	0.23693	-0.52453	0.49483
.39	1.12760	0.97855	-0.61487	0.23720	-0.52419	0.49327

TABLE 3 (cont'd)
1-3:2P COEFFICIENTS

R	$A_0 \times 10^3$	A_1	A_2	A_3	$A_4 \times 10^1$	$A_5 \times 10^2$
.40	1.11050	0.97929	-0.62069	0.24148	-0.53686	0.50692
.41	1.21970	0.97718	-0.61982	0.24070	-0.53399	0.50348
.42	0.13290	0.97741	-0.62437	0.24433	-0.54598	0.51805
.43	1.23020	0.97606	-0.62536	0.24480	-0.54612	0.51682
.44	1.19100	0.97648	-0.63029	0.24865	-0.55858	0.53160
.45	1.25920	0.97568	-0.63244	0.25010	-0.56229	0.53512
.46	1.16020	0.97599	-0.63644	0.25277	-0.56938	0.54187
.47	1.29110	0.97531	-0.63939	0.25522	-0.57754	0.55186
.48	1.22590	0.97482	-0.64198	0.25705	-0.58269	0.55729
.49	1.26780	0.97436	-0.64490	0.25916	-0.58859	0.56316
.50	0.88037	0.98069	-0.66207	0.27237	-0.63149	0.61370
.51	1.35630	0.97298	-0.64974	0.26273	-0.59899	0.57445
.52	1.39390	0.97251	-0.65249	0.26428	-0.60437	0.57989
.53	1.56550	0.97061	-0.65450	0.26750	-0.61662	0.59746
.54	1.45620	0.97180	-0.65881	0.26958	-0.61975	0.59779
.55	1.39610	0.97129	-0.66116	0.27113	-0.62353	0.60093
.56	1.52440	0.97070	-0.66454	0.27418	-0.63438	0.61487
.57	1.45420	0.97074	-0.66822	0.27690	-0.64250	0.62372
.58	1.51230	0.96951	-0.66891	0.27699	-0.64102	0.62022

TABLE 3 (cont'd)
1-3:2P COEFFICIENTS

R	$A_0 \times 10^3$	A_1	A_2	A_3	$A_4 \times 10^1$	$A_5 \times 10^2$
.59	1.54580	0.96909	-0.67179	0.27925	-0.64826	0.62890
.60	1.29670	0.97304	-0.68701	0.29329	-0.70007	0.69564
.61	1.58550	0.96830	-0.67761	0.28351	-0.66030	0.64118
.62	1.64580	0.96764	-0.68023	0.28565	-0.66713	0.64908
.63	1.69090	0.96705	-0.68272	0.28752	-0.67259	0.65501
.64	1.58780	0.96755	-0.68781	0.29187	-0.68781	0.67424
.65	1.78040	0.96555	-0.68713	0.29094	-0.68275	0.66610
.66	1.69280	0.96574	-0.69099	0.29381	-0.69143	0.67579
.67	1.72500	0.96543	-0.69417	0.29643	-0.70005	0.68609
.68	1.76970	0.96457	-0.69611	0.29800	-0.70500	0.69188
.69	1.78510	0.96428	-0.69931	0.30047	-0.71240	0.69995
.70	1.87300	0.96317	-0.70067	0.30149	-0.71503	0.70233
.71	1.89020	0.96250	-0.70246	0.30255	-0.71702	0.70328
.72	1.92640	0.96210	-0.70572	0.30541	-0.72691	0.71559
.73	1.85070	0.96211	-0.70916	0.30803	-0.73490	0.72452
.74	2.01410	0.96106	-0.71106	0.30976	-0.74079	0.73176
.75	1.91680	0.96092	-0.71407	0.31201	-0.74750	0.73913
.76	1.98610	0.95993	-0.71534	0.31279	-0.74887	0.73960
.77	2.00770	0.95981	-0.71914	0.31610	-0.76034	0.75395
.78	2.05850	0.95917	-0.72159	0.31810	-0.76647	0.76062

TABLE 3 (cont'd)
1-3:2P COEFFICIENTS

R	$A_0 \times 10^3$	A_1	A_2	A_3	$A_4 \times 10^1$	$A_5 \times 10^2$
.79	2.14880	0.95793	-0.72227	0.31840	-0.76612	0.75884
.80	2.14320	0.95825	-0.72763	0.32334	-0.78412	0.78210
.81	2.15380	0.95746	-0.72853	0.32352	-0.78281	0.77874
.82	2.11630	0.95704	-0.73116	0.32558	-0.78896	0.78526
.83	2.27160	0.95557	-0.73167	0.32598	-0.78968	0.78567
.84	2.19230	0.95559	-0.73515	0.32875	-0.79851	0.79585
.85	2.25020	0.95480	-0.73710	0.33036	-0.80345	0.80142
.86	2.28490	0.95444	-0.74010	0.33290	-0.81186	0.81156
.87	2.31220	0.95411	-0.74307	0.33537	-0.81990	0.82103
.88	2.39540	0.95293	-0.74399	0.33602	-0.82109	0.82142
.89	2.36970	0.95284	-0.74728	0.33869	-0.82970	0.83153
.90	2.47650	0.95131	-0.74725	0.33850	-0.82797	0.82834
.91	2.39460	0.95151	-0.75112	0.34167	-0.83821	0.84022
.92	2.53450	0.95060	-0.75308	0.34342	-0.84404	0.84728
.93	2.42020	0.95072	-0.75683	0.34662	-0.85500	0.86088
.94	2.49640	0.94967	-0.75778	0.34718	-0.85550	0.85991
.95	2.55890	0.94885	-0.75948	0.34854	-0.85936	0.86383
.96	2.54640	0.94891	-0.76309	0.35153	-0.86925	0.87578
.97	2.63240	0.94781	-0.76451	0.35284	-0.87333	0.88020

TABLE 3 (cont'd)
1-3:2P COEFFICIENTS

R	$A_0 \times 10^3$	A_1	A_2	A_3	$A_4 \times 10^1$	$A_5 \times 10^2$
.98	2.68180	0.94678	-0.76580	0.35409	-0.87773	0.88592
.99	2.69800	0.94670	-0.76845	0.35619	-0.88404	0.89273
1.0	2.63160	0.94641	-0.77159	0.35867	-0.89176	0.90142

VI. CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

Effectiveness values, though not analytically derived, can be determined for the 1-3:2C and 1-3:2P heat exchangers by utilizing a 5th order polynomial approximation.

Sufficient data now exists to cover a complete range of capacity rate ratios for values of N_{tu} from 0.0 to 3.25.

From the knowledge of a particular three tube pass heat exchanger arrangement and dimensions, fluid flow rates and temperature extremes, N_{tu} and R values may be computed.

Then the effectiveness may be determined using the appropriate coefficients from the tables provided herein.

After the effectiveness is obtained, there are two choices.

- 1) From a knowledge of q_{max} (see Section III), it is a simple matter to determine the actual heat transfer rate from the postulation that $q = \epsilon q_{max}$.
- 2) Both fluid outlet temperatures may be computed since $q = \omega_c C_{ph}(t_2 - t_1)$.

It is also apparent from the work done here that the 1-3:2C exchanger effectiveness outperforms that of the 1-2, 1-4 and its counter part, the 1-3:2P exchanger, as N_{tu} increases. This is true for any and all values of R . Therefore, because it is possible to determine the effectiveness of a 1-3 exchanger which has a higher effectiveness (the 1-3:2C arrangement) than that of the 1-2, 1-4 and

1-3:2P exchanger particularly at high N_{tu} levels, the 1-3 exchanger can now be given full consideration in heat exchanger design. This would be especially helpful where three tube passes could alleviate a configuration problem.

B. RECOMMENDATIONS

The following recommendations are provided for possible follow-on projects of a similar nature.

- Continue study of the $\epsilon - N_{tu}$ method for the 1-5 heat exchangers.
- Investigate the possibility of using a linear approximation from the 1-3 data to find a periodicity of R values at which to develop a 1-5 data base.
- Develop interactive software to be used on a microcomputer that contains both the 1-3 and 1-5 polynomial approximation coefficients. The procedure of entering the values for N_{tu} , R , and the type of heat exchanger when asked to do so in a menu-driven fashion so that effectiveness values can be readily obtained is self-evident.
- After results of 1-5 exchanger analyses are complete, investigate the effectiveness for both the 1-3 and 1-5 heat exchangers experimentally to confirm or refute the theoretical work done here.

THERMAL ANALYZER TVSSI COMPUTER PROGRAM

93

```

READ(4,501) NONODS,NOCT,NOHTR,INPTAG
READ(4,505) ERR,ALPHA,MNITS,BETA(1),TOLD(1)
MAXNIT = IABS(MNITS)
NIT = 0
IF(BETA(1).NE.0.) GO TO 1010
READ(4,502) (BETA(I),I=1,N)
GO TO 1030
1010 DO 1020 I=2,N
1020 BETA(I) = BETA(I-1)
C
1030 DO 15 I=1,10
INI = INPTAG(I)
IF(INI) 2,3,7,10,12,14,808,809,810,811,810,810,810) , INI
GO TO (1,2,3,7,10,12,14,808,809,810,811,810,810,810) , INI
1 NTCIN = 18*NTCOEF
2 READ(4,502) (TCOEF(K), K=1,NTCIN)
GO TO 15
2 READ(4,502) (CONTMP(K), K=1,NCT)
GO TO 15
3 READ(4,501) NOCONT
502 (HTR(K), K=1,36)
GO TO 15
7 DO 9 L=1,N
ITAG(10) = 0
READ(4,504) NT (ITAG(K), M=1, 9)
READ(4,502) (COEF(M), M=1, 9)
IF(NT=9) 8,7,10
710 DO 715 K=10,NT,9
ITAG(K+9) = 0
KE = K+8
M=K, KE)
READ(4,503) (ITAG(M), M=K, KE)
715 READ(4,502) (COEF(M), M=K, KE)
8 WRITE(1) ITAG,COEF
9 WRITE(3,556) (ITAG(KK),KK=1,30)
CONTINUE
ENDFILE 1
REWIND 1
GO TO 15
10 READ(4,502) EX
GO TO 15
12 IF (TOLD(1).NE.0.) GO TO 1201
READ(4,502) (TOLD(K), K=1,N)
GO TO 15
1201 DO 1202 L=2,N
1202 TOLD(L) = TOLD(L-1)
GO TO 15
14 K2 = 18*NTMPHT
READ(4,502) (TMPHT(K), K=1,K2)

```

```

808 GO TO 15
      READ(4,502) BTUCRV
809 GO TO 15
      READ(4,502) TMPCRV
810 GO TO 15
      WRITE(8,533) INI
      STOP
811 READ(4,502) TIMCO
15 CONTINUE
17 CALL TVPAGE (0,TITLE)
      CALL TVSOUT(N, 1,TOLD,TOLD,TITLE)

C
      WRITE(3,551) TITLE
      WRITE(3,552) N,NCT,NOHTRS,NOEXP,NOCASE,NTCOEF,NODCFH,NTMPHT,NONODS,
1 NOCT,NOHTR,MNITS
      WRITE(3,553) INPTAG,ERR,ALPHA
      WRITE(3,554) N,HEAD,(BETA(I),I=1,N)
      HEAD=HEAD1
      WRITE(3,554) N,HEAD,(TOLD(I),I=1,N)
      WRITE(3,555) (CONTMP(I),I=1,NCT)
      IF(NOHTRS) 24,24,21
20 CALL TVSHTR(NOHTRS,HTR,CASBTU,NOCONT,TOLD,NODCFH)
21 DO 107 NOD=1,N
24 DO 25 I=1,NP1
25 A(I) = 0.
      READ(1) ITAG, COEF
      DO 100 IWD=1,99
      IF (ITAG(IWD).EQ. 0) GO TO 105
      NODEI = ITAG(IWD) / 10
      METHI = MOD (ITAG(IWD) , 10)
      NTH = NODEI - NONODS
      IF ( NTH.LE. 0 ) GO TO 55
      IF ( NODEI.EQ.999 ) GO TO 50
      NNODE = NTH
      NTH = NTH - NOCT
      IF ( NTH.LE. 0 ) GO TO 60
      NNODE = NTH
      NTH = NTH - NOHTR
      IF ( NTH.LE. 0 ) GO TO 49
      IF ( NTH.GT. 5 ) GO TO 820
      IF ( NTH.LE. NTAG8 ) GO TO 815
      WRITE (9,610) NOD,NODEI,NTAG8
      IER = 1
      GO TO 100
815 A(NP1) = A(NP1) - BTUCRV(NTH)*COEF(IWD)
      GO TO 100
820 NTH = NTH - 5
      IF ( NTH.GT. 5 ) GO TO 830

```



```

85 A(NODEI) = A(NODEI) + WCOEF
GO TO 95
90 A(NP1) = A(NP1) - WCOEF*T1
95 A(NOD) = A(NOD) - WCOEF
100 CONTINUE
105 IF(NOD-NOCASE) 107,106,107
106 A(NP1) = A(NP1) - CASBTU
107 WRITE (2) (A(K),K=1,NP1)
** *
C C C C C C C C
      IF IER.NE.0 AT THIS POINT, IT MEANS THERE ARE ERRORS IN THE
      INPUT; TVSSI WILL SKIP THE CALCULATIONS AND RETURN TO
      STATEMENT 1000 FOR ANOTHER PROBLEM.
** *
C C C C C C C C
      IF ( IER.EQ.0 ) GO TO 110
      WRITE (9,670)
      GO TO 1000
C
110 ENDFILE 2
      REWIND 1
      REWIND 2
      CALL CHOST (N, NP1, H)
      ERRTAG = 0.
      NIT = NIT + 1
      IF (NIT.LT.3) GO TO 120
      CALL CBETA (N, ALPHA, BETA, TOLD, TOLD1, TOLD2, ERR)
      DO 130 I=1,N
      IF(NIT.EQ.1) TOLD1(I) = 0.0
      TOLD2(I) = TOLD1(I)
      TOLD1(I) = TOLD(I)
      TOLD(I) = TOLD(I) + BETA(I) * ( H(I) -TOLD(I))
      A(I) = TOLD(I)
      IF (ABS(A(I)).GT. ERR) ERRTAG = 1.
      CALL TVSOUT (N,2,TOLD,A,TITLE)
      IF (NOHTRS) 140,140,135
      135 LOCH = 36 + NOHTRS
      CALL TVPAGE (3,TITLE)
      WRITE (8,525) (HTR(K),K=37,LOCH)
      WRITE (8,526) CASBTU
      IF(NTCOEF) 150,150,145
      140 CALL TVPAGE (2,TITLE)
      145 WRITE (8,528) TCO(K), K= 1,NTCOEF)
      150 IF (NTMPHT) 160,160,155
      155 CALL TVPAGE (2,TITLE)
      160 WRITE (8,529) (TMPHTV(K), K=1,NTMPHT)
      IF (NIT.GE. MAXNIT .AND. MAXNIT .GT. 0) GO TO 175
      IF (ERRTAG.GT.0.) GO TO 20

```



```

2 'BUT THERE ARE ONLY 'I3,' TEMP-DEPENDENT ',
3 'COEFF CURVES (SET 1)')
650 FORMAT (/IX, I5, 5X, 'YOU SPECIFIED A CONDUCTANCE OF ', F7.1, /15X,
1 'TO NODE 'I3, 'YOU SPECIFIED A CONDUCTANCE OF ', F7.1, /15X,
2 'BUT THERE ARE ONLY 'I3, 'TIME COEFFS (SET 1)')
660 FORMAT (/IX, I5, 5X, 'YOU SPECIFIED A METHOD OF 'I3, /15X, 'TO NODE '
1 I5, 5X, 'YOU SPECIFIED A METHOD OF 'I3, /15X, 'BUT THERE ARE ONLY ',
2 I3, 'UNIQUE EXPONENTS (SET 5)')
670 FORMAT (////IX, 'THERE ARE ERRORS IN YOUR INPUT FOR THIS PROBLEM.',
1 //10X, 'TVSSI WILL SKIP ANY FURTHER CALCULATIONS FOR THIS PROBLEM.',
2 //10X, 'TVSSI WILL SKIP ANY FURTHER CALCULATIONS FOR THIS PROBLEM.',
680 FORMAT (9F8.2)
999 CONTINUE
STOP
END

```

```

C
SUBROUTINE CBETA ( N, ALPHA, BETA, TN, TNM1, TNM2, ERR )
IMPLICIT REAL*4 (A-H, O-Z)
DIMENSION TN(315), TNM1(315), TNM2(315), BETA(315)
DO 50 I=1, N
  TNM1 = TN(I) - TNM1(I)
  T12 = TNM1(I) - TNM2(I)
  IF ( ABS(T12) .LT. 1E-06 ) T12 = SIGN( 1E-06, T12 )
  GAMMA = TNM1 / T12
  IF ( GAMMA .GT. 0. ) GO TO 10
  IF ( ABS(TNM1) .LE. ERR ) GO TO 50
  IF ( GAMMA .LT. -ALPHA ) BETA(I) = -BETA(I) * ALPHA / GAMMA
  GO TO 50
10 IF ( GAMMA .GT. 1. ) GO TO 50
  BETA(I) = BETA(I) / ALPHA
50 IF ( BETA(I) .GT. 1. ) BETA(I) = 1.
RETURN
END

```

```

C
SUBROUTINE CHOST ( N, NP1, EL )
IMPLICIT REAL*4 (A-H, O-Z)
DIMENSION EL(316), LOCS(316), SAVE(49770)
LOCS(1) = 1
NP1 = N - 1
I = 0

```

```

C
10 I = I + 1
  READ (2) (EL(K), K=1, NP1)
  IP1 = I + 1
  IF ( I .EQ. 1 ) GO TO 50
  DO 45 J=2, I
    LR = LOCS(J-1)
    IF ( EL(J-1) .EQ. 0. ) GO TO 45

```

```

40 40 JR=J,NP1
   IF (SAVE(LR),EQ.0.) GO TO 40
   EL(JR) = EL(JR) - EL(J-1)*SAVE(LR)
45 LR = LR+1
50 CONTINUE
51 DO 60 K=IP1,NP1
   IF (EL(K),EQ.0.) GO TO 60
   EL(K) = EL(K) / EL(I)
60 CONTINUE
   IF (I.EQ.N) GO TO 80
   LS = LOC(I)
   LOC(I+1) = LS+NP1-I
72 DO 72 K = IP1,NP1
   SAVE(LS) = EL(K)
   LS = LS + 1
   GO TO 10
C
80 REWIND 2
   EL(N) = EL(NP1)
   DO 90 I=1,NM1
   II = NP1 - I
   LF = N - I
   LR = LOC(LF) + I
   EL(II-1) = SAVE(LR)
   DO 90 K = II,N
   K = II
   LR = LOC(LF) + K - II
   IF (SAVE(LR),EQ.0.) GO TO 90
   EL(II-1) = EL(II-1) - SAVE(LR)*EL(K)
90 CONTINUE
   RETURN
   END

```

```

C
SUBROUTINE TVFTMP (CO, T, TCOEF)
  IMPLICIT REAL*4 (A-H,O-Z)
  DIMENSION TCOEF(90)
  NC = CO - 1099.9
  NB = 18*NC - 17
  IF (T - TCOEF(NB)) 2,2,6
2  CO = TCOEF(NB+1)
  GO TO 60
6  NE = NB + 16
  NB = NB+2
  DO 50 K=NB,NE
  IF (T - TCOEF(K)) 10,20,50
10 TC = TCOEF(K)
   TCM2 = TCOEF(K-2)
   TCM1 = TCOEF(K-1)

```

```

TCP1 = TCOEF(K+1)
TCC = TC - TCM2
IF ( ABS(TCC).LT, 1E-06 ) TCC = SIGN( 1E-06, TCC )
CO = ( T - TCM2 ) / TCC ) * ( TCP1 - TCM1 ) + TCM1
GO TO 60
20 CO = TCOEF (K+1)
GO TO 60
50 CONTINUE
CO = TCOEF(NE+1)
60 RETURN
END

C
SUBROUTINE TVSOUT(N, NA, T1, T2, TITLE)
IMPLICIT REAL*4 (A-H, O-Z)
DIMENSION T1(315), T2(315), ID(12), TITLE(20)

CALL TVPAGE (2, TITLE)
WRITE (8, 500)
NL = NA+2
DO 50 I=1, N, 12 (NL, TITLE)
CALL TVPAGE (NL, TITLE)
IF (I+11-N) 5, 5, 10
5 N5=12
GO TO 15
10 N5=N-I+1
15 DO 20 K=1, N5
ID(K) = I+K-1 (ID(K), K=1, N5)
WRITE (8, 501)
N1 = I + N5 - 1
IF (NA-1) 25, 25, 30 (T1(K), K= I, N1)
25 WRITE (8, 504) (T1(K), K= I, N1)
GO TO 50
30 WRITE (8, 502) (T1(K), K= I, N1)
WRITE (8, 503) (T2(K), K= I, N1)
50 CONTINUE
RETURN

C
500 FORMAT (1H0)
501 FORMAT (/10H NODE NO. , 12I9)
502 FORMAT (12H NEW TEMPS , 12F9.2)
503 FORMAT (12H NEW - OLD , 12F9.2)
504 FORMAT (12H ORIG TEMPS , 12F9.2)
END

C
SUBROUTINE TVSHTR (NOHTRS, HTR, CASBTU, NOCONT, TOLD, NODCFH)
IMPLICIT REAL*4 (A-H, O-Z)
DIMENSION HTR(42), NOCONT(6), TOLD(315)
CASBTU = 0.

```

```

DO 25 K=1,NOHTRS
  LOK = 36+K
  IF (NOCONT(K)) 24,24,43
  LOK1 = NOCONT(K)
  TEMP = TOLD(LOK1)
  IF (K-3) 45,45,50
  LOK2 = 0
  GO TO 55
  LOK2 = 18
  IF (NODCFH) 3,3,60
  IF (TEMP-HTR(2)) 65,65,70
  HTR(LOK) = HTR(LOK2+1)
  CASBTU = CASBTU + HTR(LOK2+3)
  GO TO 25
  NODCFH = 0
  IF (TEMP - HTR(LOK2+4)) 5,5,15
  HTR(LOK) = HTR(LOK2+9)
  CASBTU = CASBTU + HTR(LOK2+14)
  GO TO 25
  DO 16 K1=5,8
  LOK3 = LOK2+K1
  IF (TEMP - HTR(LOK3)) 17,17,16
  CONTINUE
  HTR(LOK) = HTR(LOK2+13)
  CASBTU = CASBTU + HTR(LOK2+18)
  GO TO 25
  HTR3 = HTR(LOK3) - HTR(LOK3-1)
  IF (ABS(HTR3) .LT. 1E-06) HTR3 = SIGN( 1E-06, HTR3 )
  FRAC = (TEMP - HTR(LOK3-1)) / HTR3
  HTR(LOK) = (HTR(LOK3+5) - HTR(LOK3+4)) * FRAC + HTR(LOK3+4)
  CASBTU = CASBTU + (HTR(LOK3+10) - HTR(LOK3+9)) * FRAC + HTR(LOK3+9)
  GO TO 25
  HTR(LOK) = 0.
  CONTINUE
  RETURN
  END

SUBROUTINE TVPAGE (NL,FNAME)
  IMPLICIT REAL*4 (A-H,O-Z)
  DIMENSION FNAME(20)
  IF (NL) 10,10,20
  NPAGE = 0
  LINCNT = 75
  LINCNT = LINCNT + NL
  IF (LINCNT - 56) 40,40,30
  NPAGE = NPAGE + 1
  WRITE (8,50) FNAME,NPAGE
  LINCNT = NL

```

C


```

40 RETURN
50 FORMAT (1H1,20X,20A4,8X,9HPAGE NO. ,I3/)
END

/*
//GO.FT01F001 DD UNIT=SYSDA,SPACE={CYL,{1,1}}
//GO.FT02F001 DD UNIT=SYSDA,SPACE={CYL,{1,1}}
//GO.FT09F001 DD UNIT=SYSDA,SPACE={CYL,{1,1}}
//GO.FT10F001 DD UNIT=SYSDA,SPACE={CYL,{1,1}}
//GO.FT03F001 DD DUMMY
//GO.FT04F001 DD DISP=SHR,DSN=MSS.S2323.TVSSIV
//GO.FT08F001 DD SYSOUT=A,DCB=RECFM=FBA
//

```


APPENDIX B

NTU14 COMPUTER GENERATED INPUT ANALYZER PROGRAM

```

//QHARE JOB (2323 0267), 'NTU14', CLASS=B
// *MAIN ORG=NPGVM1.2323p
EXEC FORTVCL, PARM.LKED= 'LIST, MAP'
//FORT.SYSIN DD*
THIS IS PROGRAM ENTU14
CCCCCCCC
IT GENERATES AN INPUT FILE FOR THERMAL ANALYZER TO VERIFY
I-4 EFFECTIVENESS-NTU RELATIONSHIP THAT IS AVAILABLE IN
OPEN LITERATURE.
CCCCCCCC
DIMENSION COEF(250,5), KCON(250,5), L1(8), L2(3), L3(6), SET2(2), FL4(4)
CCCCCCCC
CHARACTER *79 TITLE
CHARACTER *12 FNAME
CCCCCCCC
DATA IOT, IN, IPR, IWR/6,5,4,8/
OPEN PRINTER OUTPUT FILE
CCCCCCCC
OPEN(IPR, FILE='PRN', STATUS='NEW', FORM='FORMATTED', IOSTAT=ICK)
IF(ICK.NE.0) WRITE(IOT,920)
920 FORMAT(' Trouble opening printer output file' )
CCCCCCCC
WRITE(IOT,917)
917 FORMAT(/, Input the title of this study - 79 columns only: ' page',
& , This title, will appear',/, at the top of every printed page',
& , of output:')
918 READ(IN,918) TITLE
918 FORMAT(A79)
CCCCCCCC
WRITE(IOT,901)
901 FORMAT(/, INPUT HOT SIDE CAPACITY RATE:')
902 READ(IN,902) CHOT
902 FORMAT(BN,F10.0)
CCCCCCCC
WRITE(IOT,903)
903 FORMAT(/, INPUT COLD SIDE CAPACITY RATE:')
904 READ(IN,902) CCLD
904 FORMAT(BN,F10.0)
CCCCCCCC
WRITE(IOT,904)

```

```

904 FORMAT(/, ' INPUT OVERALL HEAT TRANSFER COEFFICIENT:')
   C READ(IN, 902) U

905 WRITE(IOT, 905)
   C FORMAT(/, ' INPUT TOTAL HEAT TRANSFER SURFACE:')
   C READ(IN, 902) SURFTO

906 WRITE(IOT, 906)
   C FORMAT(/, ' INPUT HOT SIDE INLET TEMPERATURE:')
   C READ(IN, 902) THOTIN

907 WRITE(IOT, 907)
   C FORMAT(/, ' INPUT COLD SIDE INLET TEMPERATURE:')
   C READ(IN, 902) TCLDIN

   C VALK1 = CHOT
   C VALK2 = CCLD

60 TINIT = 100.
   C

   C FRONT END
   C
   C L1{1} = 250
   C L1{2} = 2
   C DO 10 I=3, 8
   C 10 L1(I) = 0

   C DO 20 I=1, 3
   C 20 L2(I) = 0

   C L3{1} = 300
   C L3{2} = 50
   C L3{3} = 6
   C L3{4} = 2
   C L3{5} = 4
   C L3{6} = 6

   C FL4{1} = .05
   C FL4{2} = .66667
   C FL4{3} = .8
   C FL4{4} = TINIT
   C L4 = 12

   C CONSTANT TEMPERATURES
   C
   C SET2{1} = THOTIN
   C SET2{2} = TCLDIN

```

```

CCCCC      READY FOR INPUT SET 4
      NODE 1
      KCON(1,1) = 514
      KCON(1,2) = 1504
      KCON(1,3) = 1514
      KCON(1,4) = 2504
      KCON(1,5) = 3015
      COEF(1,5) = VALK1
      DO 50 I = 1,4
50 COEF(I,1) = VALK3
      NODES 2 TO 50
      DO 75 I = 2,50
      J = I + 50
      K = 151 - I
      L = 150 - I
      M = 251 - I
      N = I - 1
      KCON(I,1) = 10*N + 2
      KCON(I,2) = 10*J + 2
      KCON(I,3) = 10*K + 2
      KCON(I,4) = 10*L + 2
      KCON(I,5) = 10*M + 2
      COEF(I,1) = VALK1
      DO 80 I,11
80 COEF(I,11) = VALK3
      CONTINUE
75 CONTINUE
      NODE 51
      KCON(51,1) = 3025
      KCON(51,2) = 14
      COEF(51,1) = VALK2
      COEF(51,2) = VALK3
      NODES 52 TO 250
      DO 120 I = 52,250
      K = I - 1
      IF(I.GT.100) GO TO 122
      J = I - 50
      GO TO 135
122 IF(I.GT.150) GO TO 124
      L = I - 100

```

```

M = 2*L - 1
N = M + 50
J = I - N
GO TO 135
124 IF (I.GT.200) GO TO 126
J = I - 150
GO TO 135
126 CONTINUE
L = I - 200
M = 2*L - 1
N = M + 150
J = I - N
135 KCON(I,1) = 10*J + 4
KCON(I,2) = 10*K + 5
COEF(I,1) = VALK3
120 COEF(I,2) = VALK2

C      END OF DATA SETUP
C      NOW CREATE INPUT FOR ANALYZER
C
WRITE(IOT, 922)
922 FORMAT(/, 'Enter name of input file, including drive',
& ' DESIGNATION: ')
923 READ(IN, 923) FNAME
FORMAT(A12)

C      OPEN INPUT FILE
C
OPEN(IWR, FILE=FNAME, STATUS='NEW', FORM='FORMATTED', IOSTAT=ICK)
IF(ICK.GT.0) WRITE(IOT, 924)
924 FORMAT(/, 'Trouble opening input file')

C
WRITE(IOT, 925) FNAME
925 FORMAT(/, 'Writing file : ', A14)
WRITE(IWR, 919) TITLE
919 FORMAT(1X, A79)
WRITE(IWR, 908) (L1(I), I=1, 8)
908 FORMAT(9I4)
WRITE(IWR, 908) (L2(I), I=1, 3)
WRITE(IWR, 908) (L3(I), I=1, 6)
WRITE(IWR, 911) FL4(1), FL4(2), L4, FL4(3), FL4(4)
911 FORMAT(F8.3, F8.5, I8, 2F8.1)
WRITE(IWR, 912) SET2(1), SET2(2)
912 FORMAT(2F8.0)

C
DO 200 I = 1, 50
WRITE(IWR, 913) (KCON(I, J), J=1, 5)
913 FORMAT(9I8)

```

```

WRITE(IWR,914)(COEF(I,J),J=1,5)
914 FORMAT(5F8.4)
200 CONTINUE
C
DO 250 I=51,250
WRITE(IWR,913) KCON(I,1),KCON(I,2)
WRITE(IWR,914) COEF(I,1),COEF(I,2)
250 CONTINUE
C
7 CONTINUE
STOP
END
/*
//LKED.SYSLMOND DD DISP=SHR,DSNAME=MSS.S2323.LOAD
//LKED.SYSIN DD *
/*
//NAME NTU14(R)
//

```

NTU32C COMPUTER GENERATED INPUT ANALYZER PROGRAM

110

```

905 WRITE(IOT,905)
  FORMAT(/,INPUT TOTAL HEAT TRANSFER SURFACE:')
  READ(IN,902) SURFTO
C
906 WRITE(IOT,906)
  FORMAT(/,INPUT HOT SIDE INLET TEMPERATURE:')
  READ(IN,902) THOTIN
C
907 WRITE(IOT,907)
  FORMAT(/,INPUT COLD SIDE INLET TEMPERATURE:')
  READ(IN,902) TCLDIN
C
  VALK1 = CHOT
  VALK2 = CCLD
  VALK3 = U*SURFTO/150.
  TINIT = 125.
C
C      FRONT END
C
  L1{1} = 200
  L1{2} = 2
  DO 10 I=3,8
10  L1(I) = 0
C
  DO 20 I=1,3
20  L2(I) = 0
C
  L3{1} = 300
  L3{2} = 50
  L3{3} = 6
  L3{4} = 2
  L3{5} = 4
  L3{6} = 6
C
  FL4{1} = .05
  FL4{2} = .66667
  FL4{3} = .8
  FL4{4} = TINIT
  L4 = L2
C
C      CONSTANT TEMPERATURES
C
  SET2{1} = THOTIN
  SET2{2} = TCLDIN
C
  READY FOR INPUT SET 4
C
C      NODE 1

```



```

135 KCON(I,1) = 10*I + 4
    KCON(I,2) = 10*K + 5
    COEF(I,1) = VALK3
120 COEF(I,2) = VALK2

    END OF DATA SETUP
    NOW CREATE INPUT FOR ANALYZER

    WRITE(IOT, 922)
    922 FORMAT(/, ENTER NAME OF INPUT FILE, INCLUDING DRIVE',
    & ' DESIGNATION:')
    923 READ(IN, 923) FNAME
    FORMAT(A12)

    OPEN INPUT FILE

    OPEN(IWR, FILE='TVSSI', STATUS='NEW', FORM='FORMATTED', IOSTAT=ICK)
    IF(ICK.GT.0) WRITE(IOT, 924)
    924 FORMAT(/, Trouble opening input file')

    WRITE(IOT, 925) FNAME
    WRITE(IOT, 925)
    925 FORMAT(/, WRITING FILE : 'A14')
    925 FORMAT(/, WRITING FILE : 'TVSSI')
    WRITE(IWR, 919) TITLE
    919 FORMAT(1X, A79)
    WRITE(IWR, 908) (L1(I), I=1, 8)
    908 FORMAT(9I4)
    WRITE(IWR, 908) (L2(I), I=1, 3)
    WRITE(IWR, 908) (L3(I), I=1, 6)
    WRITE(IWR, 911) FL4(1), FL4(2), L4, FL4(3), FL4(4)
    911 FORMAT(F8.3, F8.5, I8.2, F8.1)
    912 WRITE(IWR, 912) SET2(1), SET2(2)
    FORMAT(2F8.0)

    DO 200 I = 1, 50
    WRITE(IWR, 913) (KCON(I, J), J=1, 4)
    913 FORMAT(9I8)
    WRITE(IWR, 914) (COEF(I, J), J=1, 4)
    914 FORMAT(4F8.4)
    200 CONTINUE

    DO 250 I=51, 200
    WRITE(IWR, 913) KCON(I, 1), KCON(I, 2)
    WRITE(IWR, 914) COEF(I, 1), COEF(I, 2)
    250 CONTINUE

    CLOSE (IWR, IOSTAT=ICK)

```

```
C      921 IF(ICK_NE.0) WRITE(IOT,921)EEX  
        FORMAT(' Trouble closing printer output file' )  
        STOP  
        END
```

NTU32P COMPUTER GENERATED INPUT ANALYZER PROGRAM

115

```

905 WRITE(IOT,905)
   FORMAT(/,INPUT TOTAL HEAT TRANSFER SURFACE:')
   READ(IN,902) SURFTO
C
906 WRITE(IOT,906)
   FORMAT(/,INPUT HOT SIDE INLET TEMPERATURE:')
   READ(IN,902) THOTIN
C
907 WRITE(IOT,907)
   FORMAT(/,INPUT COLD SIDE INLET TEMPERATURE:')
   READ(IN,902) TCLDIN
C
   VALK1 = CHOT
   VALK2 = CCLD
   VALK3 = U*SURFTO/150.
   TINIT = 125.
C
C      FRONT END
C
   L1{1} = 200
   L1{2} = 2
   DO 10 I=3,8
10  L1(I) = 0
C
   DO 20 I=1,3
20  L2(I) = 0
C
   L3{1} = 300
   L3{2} = 50
   L3{3} = 6
   L3{4} = 2
   L3{5} = 4
   L3{6} = 6
C
   FL4{1} = .05
   FL4{2} = .66667
   FL4{3} = .8
   FL4{4} = TINIT
   L4 = L2
C
C      CONSTANT TEMPERATURES
C
   SET2{1} = THOTIN
   SET2{2} = TCLDIN
C
C      READY FOR INPUT SET 4
C
C      NODE 1

```



```

      KCON(I,2) = 10*K + 5
      COEF(I,1) = VALK3
      COEF(I,2) = VALK2
120 CONTINUE
C
C      END OF DATA SETUP
C      NOW CREATE INPUT FOR ANALYZER
C
      WRITE(IOT,922)
922 FORMAT(/, 'Enter name of input file, including drive',
      & ' DESIGNATION:')
      READ(IN,923) FNAME
923 FORMAT(A12)
C
      OPEN INPUT FILE
C
      OPEN(IWR, FILE=FNAME, STATUS='NEW', FORM='FORMATTED', IOSTAT=ICK)
      IF(ICK.GT.0) WRITE(IOT,924)
924 FORMAT(/, 'Trouble opening input file')
C
      WRITE(IOT,925) FNAME
925 FORMAT(/, 'Writing file:', A14)
919 FORMAT(1X, A79)
908 WRITE(IWR,908) (L1(I), I=1,8)
      WRITE(IWR,908) (L2(I), I=1,3)
      WRITE(IWR,908) (L3(I), I=1,6)
      WRITE(IWR,911) FL4(1), FL4(2), L4, FL4(3), FL4(4)
911 FORMAT(F8.3, F8.5, F8.2)
912 WRITE(IWR,912) SET2(1), SET2(2)
      FORMAT(2F8.0)
C
      DO 200 I = 1, 50
        WRITE(IWR,913) (KCON(I,J), J=1,4)
913 FORMAT(9I8)
        WRITE(IWR,914) (COEF(I,J), J=1,4)
914 FORMAT(4F8.4)
200 CONTINUE
C
      DO 250 I=51,200
        WRITE(IWR,913) KCON(I,1), KCON(I,2)
        WRITE(IWR,914) COEF(I,1), COEF(I,2)
250 CONTINUE
C
      CLOSE(IWR, IOSTAT=ICK)
      IF(ICK.NE.0) WRITE(IOT,921)EEX
921 FORMAT('Trouble closing printer output file' )
C

```


STOP
END

APPENDIX E

SAMPLE OUTPUT FROM NTU14 COMPUTER INPUT ANALYZER PROGRAM

NTU=0.05	R=0.15	COUNTER	0	0	0
200	2	0	0	0	0
300	0	4	6	12	0.80000
0	0.66667	2	12	0.80000	125.00
0.050	0.66667	2004	3015		
1004	1014	0.0125	250.0000		
0.0125	0.0125	1024	1994		
250.0000	0.0125	0.0125	0.0125		
250.0000	0.0125	1034	1984		
250.0000	0.0125	0.0125	0.0125		
250.0000	0.0125	1044	1974		
250.0000	0.0125	0.0125	0.0125		
250.0000	0.0125	1054	1964		
250.0000	0.0125	0.0125	0.0125		
250.0000	0.0125	1064	1954		
250.0000	0.0125	0.0125	0.0125		
250.0000	0.0125	1074	1944		
250.0000	0.0125	0.0125	0.0125		
250.0000	0.0125	1084	1934		
250.0000	0.0125	0.0125	0.0125		
250.0000	0.0125	1094	1924		
250.0000	0.0125	0.0125	0.0125		
250.0000	0.0125	1104	1914		
250.0000	0.0125	0.0125	0.0125		
250.0000	0.0125	1114	1904		
250.0000	0.0125	0.0125	0.0125		
250.0000	0.0125	1124	1894		
250.0000	0.0125	0.0125	0.0125		
250.0000	0.0125	1134	1884		
250.0000	0.0125	0.0125	0.0125		
250.0000	0.0125	1144	1874		
250.0000	0.0125	0.0125	0.0125		
250.0000	0.0125	1154	1864		
250.0000	0.0125	0.0125	0.0125		
250.0000	0.0125	1164	1854		
250.0000	0.0125	0.0125	0.0125		
250.0000	0.0125	1174	1844		
250.0000	0.0125	0.0125	0.0125		
250.0000	0.0125	1184	1834		
250.0000	0.0125	0.0125	0.0125		

250.0000	185	0.0125	1194	0.0125	1824
250.0000	195	0.0125	1125	0.0125	0.0125
250.0000	205	0.0125	1204	0.0125	0.0125
250.0000	215	0.0125	0.0125	0.0125	0.0125
250.0000	225	0.0125	0.0125	0.0125	0.0125
250.0000	235	0.0125	0.0125	0.0125	0.0125
250.0000	245	0.0125	0.0125	0.0125	0.0125
250.0000	255	0.0125	0.0125	0.0125	0.0125
250.0000	265	0.0125	0.0125	0.0125	0.0125
250.0000	275	0.0125	0.0125	0.0125	0.0125
250.0000	285	0.0125	0.0125	0.0125	0.0125
250.0000	295	0.0125	0.0125	0.0125	0.0125
250.0000	305	0.0125	0.0125	0.0125	0.0125
250.0000	315	0.0125	0.0125	0.0125	0.0125
250.0000	325	0.0125	0.0125	0.0125	0.0125
250.0000	335	0.0125	0.0125	0.0125	0.0125
250.0000	345	0.0125	0.0125	0.0125	0.0125
250.0000	355	0.0125	0.0125	0.0125	0.0125
250.0000	365	0.0125	0.0125	0.0125	0.0125
250.0000	375	0.0125	0.0125	0.0125	0.0125
250.0000	385	0.0125	0.0125	0.0125	0.0125
250.0000	395	0.0125	0.0125	0.0125	0.0125
250.0000	405	0.0125	0.0125	0.0125	0.0125
250.0000	415	0.0125	0.0125	0.0125	0.0125
250.0000		0.0125	0.0125	0.0125	0.0125

250.0000	425	584	1434	1584
250.0000	435	0.0125	0.0125	0.0125
250.0000	445	0.0125	0.0125	0.0125
250.0000	455	0.0125	0.0125	0.0125
250.0000	465	0.0125	0.0125	0.0125
250.0000	475	0.0125	0.0125	0.0125
250.0000	485	0.0125	0.0125	0.0125
250.0000	495	0.0125	0.0125	0.0125
250.0000	505	0.0125	0.0125	0.0125
37.5000	494	0.0125	0.0125	0.0125
0.0125	484	37.5000	0.0125	0.0125
0.0125	474	37.5000	0.0125	0.0125
0.0125	464	37.5000	0.0125	0.0125
0.0125	454	37.5000	0.0125	0.0125
0.0125	444	37.5000	0.0125	0.0125
0.0125	434	37.5000	0.0125	0.0125
0.0125	424	37.5000	0.0125	0.0125
0.0125	414	37.5000	0.0125	0.0125
0.0125	404	37.5000	0.0125	0.0125
0.0125	394	37.5000	0.0125	0.0125
0.0125	384	37.5000	0.0125	0.0125
0.0125	374	37.5000	0.0125	0.0125
0.0125	364	37.5000	0.0125	0.0125
0.0125	354	37.5000	0.0125	0.0125
0.0125	344	37.5000	0.0125	0.0125

0.0125	344	665
0.0125	37.5000	665
0.0125	37.5000	675
0.0125	37.5000	685
0.0125	37.5000	695
0.0125	37.5000	705
0.0125	37.5000	715
0.0125	37.5000	725
0.0125	37.5000	735
0.0125	37.5000	745
0.0125	37.5000	755
0.0125	37.5000	765
0.0125	37.5000	775
0.0125	37.5000	785
0.0125	37.5000	795
0.0125	37.5000	805
0.0125	37.5000	815
0.0125	37.5000	825
0.0125	37.5000	835
0.0125	37.5000	845
0.0125	37.5000	855
0.0125	37.5000	865
0.0125	37.5000	875
0.0125	37.5000	885
0.0125	37.5000	895
0.0125	37.5000	905

[illegible]

0.0	125	154	37.	145
0.0	125	164	37.	500
0.0	125	174	37.	155
0.0	125	184	37.	500
0.0	125	194	37.	165
0.0	125	204	37.	500
0.0	125	214	37.	175
0.0	125	224	37.	500
0.0	125	234	37.	185
0.0	125	244	37.	500
0.0	125	254	37.	195
0.0	125	264	37.	500
0.0	125	274	37.	205
0.0	125	284	37.	500
0.0	125	294	37.	1205
0.0	125	304	37.	500
0.0	125	314	37.	500
0.0	125	324	37.	1285
0.0	125	334	37.	500
0.0	125	344	37.	500
0.0	125	354	37.	1305
0.0	125	364	37.	500
0.0	125	374	37.	1315
0.0	125	384	37.	500
0.0	125	394	37.	1325
0.0	125	404	37.	500
0.0	125	414	37.	1335
0.0	125	424	37.	500
0.0	125	434	37.	1345
0.0	125	444	37.	500
0.0	125	454	37.	1355
0.0	125	464	37.	500
0.0	125	474	37.	1365
0.0	125	484	37.	500
0.0	125	494	37.	1375
0.0	125	504	37.	500

0.0125	394	37.5000	1385
0.404		37.1395	
0.0125		37.5000	
0.414		37.1405	
0.0125		37.5000	
0.424		37.1415	
0.0125		37.5000	
0.434		37.1425	
0.0125		37.5000	
0.444		37.1435	
0.0125		37.5000	
0.454		37.1445	
0.0125		37.5000	
0.464		37.1455	
0.0125		37.5000	
0.474		37.1465	
0.0125		37.5000	
0.484		37.1475	
0.0125		37.5000	
0.494		37.1485	
0.0125		37.5000	
0.504		37.1495	
0.0125		37.5000	
0.504		37.1505	
0.0125		37.5000	
0.494		37.1515	
0.0125		37.5000	
0.484		37.1525	
0.0125		37.5000	
0.474		37.1535	
0.0125		37.5000	
0.464		37.1545	
0.0125		37.5000	
0.454		37.1555	
0.0125		37.5000	
0.444		37.1565	
0.0125		37.5000	
0.434		37.1575	
0.0125		37.5000	
0.424		37.1585	
0.0125		37.5000	
0.414		37.1595	
0.0125		37.5000	
0.404		37.1605	
0.0125		37.5000	
0.394		37.1615	
0.0125		37.5000	

0.0	384	37.	1625
0.0	125	37.	5000
0.0	374	37.	1635
0.0	125	37.	5000
0.0	364	37.	1645
0.0	125	37.	5000
0.0	354	37.	1655
0.0	125	37.	5000
0.0	344	37.	1665
0.0	125	37.	5000
0.0	334	37.	1675
0.0	125	37.	5000
0.0	324	37.	1685
0.0	125	37.	5000
0.0	314	37.	1695
0.0	125	37.	5000
0.0	304	37.	1705
0.0	125	37.	5000
0.0	294	37.	1715
0.0	125	37.	5000
0.0	284	37.	1725
0.0	125	37.	5000
0.0	274	37.	1735
0.0	125	37.	5000
0.0	264	37.	1745
0.0	125	37.	5000
0.0	254	37.	1755
0.0	125	37.	5000
0.0	244	37.	1765
0.0	125	37.	5000
0.0	234	37.	1775
0.0	125	37.	5000
0.0	224	37.	1785
0.0	125	37.	5000
0.0	214	37.	1795
0.0	125	37.	5000
0.0	204	37.	1805
0.0	125	37.	5000
0.0	194	37.	1815
0.0	125	37.	5000
0.0	184	37.	1825
0.0	125	37.	5000
0.0	174	37.	1835
0.0	125	37.	5000
0.0	164	37.	1845
0.0	125	37.	5000
0.0	154	37.	1855
0.0	125	37.	5000

0.0125	144	37.5000	1865
0.0134	134	37.5000	1875
0.0125	125	37.5000	1885
0.0124	124	37.5000	1895
0.0114	114	37.5000	1905
0.0125	104	37.5000	1915
0.0125	94	37.5000	1925
0.0125	84	37.5000	1935
0.0125	74	37.5000	1945
0.0125	64	37.5000	1955
0.0125	54	37.5000	1965
0.0125	44	37.5000	1975
0.0125	34	37.5000	1985
0.0125	24	37.5000	1995
0.0125	14	37.5000	2000

MODIFIED SECTIONS OF THERMAL ANALYZER TO RUN ON BATCH SYSTEM

129

```

REWIND 1
READ 2
READ(4,501) N,NCT,NOHTRS,NOEXP,NOCASE,NTCOEF,NODCFH,NTMPHT
NPI = N + 1
READ(4,501) NTAG8,NTAG9,NTAG11
READ(4,501) NONODS,NOCT,NOHTR,INPTAG
READ(4,505) ERR,ALPHA,MNITS,BETA(1),TOLD(1)
MAXNIT = IABS(MNITS)
NIT = 0
IF(BETA(1).NE.0.) GO TO 1010
READ(4,502) (BETA(I),I=1,N)
GO TO 1030
1010 DO 1020 I=2,N
1020 BETA(I) = BETA(I-1)
C
1030 DO 15 I=1,10
INI = INPTAG(I)
IF(INI) 17,17,6
GO TO (1,2,3,7,10,12,14,808,809,810,811,810,810,810), INI
6
1 NTCIN = 18*NTCOEF
1 READ(4,502) (TCOEF(K), K=1,NTCIN)
GO TO 15
2 READ(4,502) (CONTMP(K), K=1,NCT)
GO TO 15
3 READ(4,501) NOCONT
3 READ(4,502) (HTR(K), K=1,36)
GO TO 15
7 DO 9 L=1,N
ITAG(10) = 0
READ(4,504) NT, (ITAG(K), M=1, 9)
READ(4,502) (COEF(M), M=1, 9)
IF(NT-9) 8,710
710 DO 715 K=10,NT,9
ITAG(K+9) = 0
KE = K+8
M=K, KE)
READ(4,503) (ITAG(M), M=K, KE)
715 READ(4,502) (COEF(M), M=K, KE)
8 WRITE(1,1) ITAG,COEF
9 WRITE(3,556) (ITAG(KK),KK=1,30)
9 CONTINUE
ENDFILE 1
REWIND 1
GO TO 15
10 READ(4,502) EX
GO TO 15
12 IF (TOLD(1).NE.0.) GO TO 1201
12 READ(4,502) (TOLD(K), K=1,N)
GO TO 15

```

```

1201 DO 1202 L=2,N
1202 TOLD(L) = TOLD(L-1)
      GO TO 15
14 K2 = 18*NTMPHT
   READ(4,502) (TMPHT(K), K=1,K2)
   GO TO 15
808 READ(4,502) BTUCRV
   GO TO 15
809 READ(4,502) TMPCRV
   GO TO 15
810 WRITE (8,533) INI
      STOP
811 READ(4,502) TIMCO
15 CONTINUE
17 CALL TVPAGE (0,TITLE)
   CALL TVSOUT(N, 1,TOLD,TOLD,TITLE)

C
   WRITE(3,551) TITLE
   WRITE(3,552) N,NCT,NOHTRS,NOEXP,NOCASE,NTCOEF,NODCFH,NTMPHT,NONODS,
1 NOCT,NOHTR,MNITS
   WRITE(3,553) INPTAG,ERR,ALPHA
   WRITE(3,554) N,HEAD,(BE1A(I), I=1,N)
   HEAD=HEAD1
   WRITE(3,554) N,HEAD,(TOLD(I), I=1,N)
   WRITE(3,555) (CONTMP(I), I=1,NCT)
20 IF(NOHTRS) 24,24,21
21 CALL TVSHTR(NOHTRS,HTR,CASBTU,NOCONT,TOLD,NODCFH)
24 DO 107 NOD=1,N
25 A(I) = 0.
   READ(1) ITAG, COEF
   DO 100 IWD=1,99
   IF (ITAG(IWD) .EQ. 0) GO TO 105
   NODEI = ITAG(IWD) / 10
   METHI = MOD (ITAG(IWD), 10)
   NTH = NODEI - NONODS
   IF (NTH.LE.0) GO TO 55
   IF (NODEI.EQ.999) GO TO 50
   NNODE = NTH
   NTH = NTH - NOCT
   IF (NTH.LE.0) GO TO 60
   NNODE = NTH
   NTH = NTH - NOHTR
   IF (NTH.LE.0) GO TO 49
   IF (NTH.GT.5) GO TO 820
   IF (NTH.LE.NTAG8) GO TO 815
   WRITE (9,610) NOD,NODEI,NTAG8
   IER = 1

```

```

815 GO TO 100
   A(NP1) = A(NP1) - BTUCRV(NTTH)*COEF(IWD)
820 GO TO 100
   NTTH = NTTH - 5
   IF ( NTTH.GT.5 ) GO TO 830
   IF ( NTTH.LE.NTAG9 ) GO TO 825
   WRITE (9,620) NOD,NODEI,NTAG9
   IER = 1
   GO TO 100
825 T1 = TMPCRV(NTTH)
   GO TO 65
830 NTTH = NTTH - 5
   IF ( NTTH.LE.5 ) GO TO 48
   WRITE (9,570) NOD,NODEI
   IER = 1
   GO TO 100
48 IF ( NTTH.LE.NTMPHT ) GO TO 480
   WRITE (9,630) NOD,NODEI,NTMPHT
   IER = 1
   GO TO 100
480 WCOEF = NTTH + 1100
   CALL TVFTMP (WCOEF, TOLD(NOD), TMPHT)
   A(NP1) = A(NP1) - WCOEF*COEF(IWD)
   TMPHTV(NTTH) = WCOEF
   GO TO 100
49 IF ( NNODE.LE.NOHTRS ) GO TO 490
   WRITE (9,600) NOD,NODEI,NOHTRS
   IER = 1
   GO TO 100
490 LOCH = 36 + NNODE
   A(NP1) = A(NP1) - HTR(LOCH) * COEF(IWD)
   GO TO 100
50 A(NP1) = A(NP1) - COEF(IWD)
   GO TO 100
55 T1 = TOLD(NODEI)
   GO TO 65
60 IF ( NNODE.LE.NCT ) GO TO 61
   WRITE (9,590) NOD,NODEI,NCT
   IER = 1
   GO TO 100
61 T1 = CONTMP(NNODE)
65 T2 = TOLD(NOD)
   WCOEF = COEF(IWD)
   *

```

C C C C C

ASSUMING THE USER HAS RUN PROGRAM CHECK AND FIXED ANY WCOEFS
 THAT MIGHT HAVE BEEN IN ERROR. TVSSI, THEREFORE, WILL NOT
 CHECK AGAIN FOR A WCOEF > 100. NO WARNING IS PRINTED.

* * *


```

IF ( WCOEF.LE.1000. ) GO TO 73
IF ( WCOEF.LE.1005. ) GO TO 850
IF ( WCOEF.LE.1100. ) GO TO 73
IF ( WCOEF.GT.1105. ) GO TO 73
ATEMP = (T1+T2)/2
LC = WCOEF - 1099.99
IF ( LC.LE.NTCOEF ) GO TO 840
WRITE (9,640) NOD,NODEI,WCOEF,NTCOEF
IER = 1
GO TO 100
840 CALL TVFTMP (WCOEF, ATEMP, TCOEF)
TCO(LC) = WCOEF
GO TO 73
850 LC = WCOEF - 999.99
IF ( LC.LE.NTAG11 ) GO TO 855
WRITE (9,650) NOD,NODEI,WCOEF,NTAG11
IER = 1
GO TO 100
855 WCOEF = TIMCO(LC)
C C C C C
* * THE FOLLOWING COMPUTED GO TO WILL FALL THROUGH TO THE NEXT
STATEMENT FOR METHODS 6,7,8,& 9
73 GO TO (80,730,730,80,80), METHI
730 TD = T1-T2
IF (TD.NE.0. ) GO TO 731
WCOEF = 0.
GO TO 80
731 IF (ABS(TD).LT.1E-05 ) TD = SIGN( 1E-05,TD )
ABSTD = ABS(TD)
GO TO (80,74,75,80,80), METHI
LC = METHI - 5
IF ( LC.LE.NOEXP ) GO TO 77
WRITE (9,660) NOD,NODEI,METHI,NOEXP
IER = 1
GO TO 100
77 T3 = EX (LC)
C C C C C
* * THE FOLLOWING STATEMENT EQUATES TO
WCOEF = WCOEF *((ABSTD **T3)/ABSTD)
GO TO 80
C C C C C
* * WCOEF = WCOEF * ABSTD ** (T3-1.)
GO TO 80
C C C C C
* * THE FOLLOWING STATEMENT EQUATES TO
WCOEF = WCOEF *((ABSTD **1.25)/ABSTD)
C C C C C
74 WCOEF = WCOEF * ABSTD ** .25

```



```

630 FORMAT (/1X,'** * INVALID NODE - - YOU SPECIFIED AN ',
1,'INTERACTION FROM NODE',I5,5X,'TO A NODE',I5,5X,
2,'BUT THERE ARE ONLY',I4,5X,'TEMP-DEPENDENT WATT CURVES (SET 7)')
640 FORMAT (/1X,'** * INVALID CONDUCTANCE - - NODE',I5,5X,
1,'TO NODE',I5,5X,'YOU SPECIFIED A CONDUCTANCE OF',F7.1,5X,
2,'BUT THERE ARE ONLY',I3,5X,'TEMP-DEPENDENT',
3,'COEFF CURVES (SET 1)')
650 FORMAT (/1X,'** * INVALID CONDUCTANCE - - NODE',I5,5X,
1,'TO NODE',I5,5X,'YOU SPECIFIED A CONDUCTANCE OF',F7.1,5X,
2,'BUT THERE ARE ONLY',I3,5X,'TIME COEFFS (SET 11)')
660 FORMAT (/1X,'** * INVALID METHOD - - NODE',I5,5X,'TO NODE',
1,I5,5X,'YOU SPECIFIED A METHOD OF',I3,5X,'BUT THERE ARE ONLY',
2,I3,5X,'UNIQUE EXPONENTS (SET 5)')
670 FORMAT (////1X,'THERE ARE ERRORS IN YOUR INPUT FOR THIS PROBLEM',
1'//10X,'TVSSI WILL SKIP ANY FURTHER CALCULATIONS FOR THIS PROBLEM',
2'////////')
680 FORMAT(9F8.2)
999 CONTINUE
STOP
END

```

C

```

SUBROUTINE CBETA ( N, ALPHA, BETA, TN, TNM1, TNM2, ERR )
IMPLICIT REAL*4 (A-H,O-Z)
DIMENSION TN(315), TNM1(315), TNM2(315), BETA(315)
DO 50 I=1,N
  TMTM1 = TN(I) - TNM1(I)
  T12 = TNM1(I) - TNM2(I)
  IF ( ABS(T12) .LT. 1E-06 ) T12 = SIGN( 1E-06, T12 )
  GAMMA = TMTM1 / T12
  IF ( GAMMA .GT. 0. ) GO TO 10
  IF ( ABS(TMTM1) .LE. ERR ) GO TO 50
  IF ( GAMMA .LT. -ALPHA ) BETA(I) = -BETA(I)*ALPHA/GAMMA
  GO TO 50
10 IF ( GAMMA .GT. 1. ) GO TO 50
  BETA(I) = BETA(I) / ALPHA
50 IF ( BETA(I) .GT. 1. ) BETA(I) = 1.
RETURN
END

```

C

```

SUBROUTINE CHOST (N,NP1,EL)
IMPLICIT REAL*4 (A-H,O-Z)
DIMENSION EL(316), LOCS(316), SAVE(49770)
LOCS(1) = 1
NM1 = N - 1
I = 0

```

C

```

10 I = I + 1
READ (2) (EL(K), K=1, NP1)

```

```

40 IP1 = I + 1
45 IF (I.EQ. 1) GO TO 50
DO 45 J=2,I
LR = LOCS(J-1)EQ. 0. ) GO TO 45
IF (EL(J-1)EQ. 0. ) GO TO 40
DO 40 JR=J,NP1
IF (SAVE(LR)EQ. 0. ) GO TO 40
EL(JR) = EL(JR) - EL(J-1)*SAVE(LR)
LR = LR+1
45 CONTINUE
50 CONTINUE
51 DO 60 K=IP1,NP1
IF (EL(K)EQ. 0. ) GO TO 60
EL(K) = EL(K) / EL(I)
60 CONTINUE
IF (I.EQ. N) GO TO 80
LS = LOCS(I)
LOCS(I+1) = LS+NP1-I
DO 72 K=IP1,NP1
SAVE(LS) = EL(K)
72 LS = LS + 1
GO TO 10

```

C

```

80 REWIND 2
EL(N) = EL(NP1)
DO 90 I=1,NM1
II = NP1 - I
LF = N - I
LR = LOCS(LF) + I
EL(II-1) = SAVE(LR)
DO 90 K=II,N
IF (LOCS(LF) + K - II GO TO 90
IF (SAVE(LR)EQ. 0. )
EL(II-1) = EL(II-1) - SAVE(LR)*EL(K)
90 CONTINUE
RETURN
END

```

C

```

SUBROUTINE TVFTMP (CO, T, TCOEF)
IMPLICIT REAL*4 (A-H, O-Z)
DIMENSION TCOEF(90)
NC = CO - 1099.9
NB = 18*NC - 17
IF (T - TCOEF(NB)) 2, 2, 6
CO = TCOEF(NB+1)
2 CO TO 60
6 NE = NB + 16
NB = NB+2

```

```

10 DO 50 K=NB,NE,2 10,20,50
IF (T-TCOEF(K))2
TC = TCOEF(K)
TCM2 = TCOEF(K-2)
TCM1 = TCOEF(K-1)
TCP1 = TCOEF(K+1)
TCC = TC - TCM2
IF (ABS(TCC).LT,1E-06) TCC = SIGN(1E-06,TCC)
CO = (T - TCM2)/TCC * (TCP1 - TCM1) + TCM1
GO TO 60
20 CO = TCOEF(K+1)
GO TO 60
50 CONTINUE
60 CO = TCOEF(NE+1)
RETURN
END

C
SUBROUTINE TVSOUT(N,NA,T1,T2,TITLE)
IMPLICIT REAL*4(A-H,O-Z)
DIMENSION T1(315),T2(315),ID(12),TITLE(20)

CALL TVPAGE(2,TITLE)
WRITE(8,500)
NL = NA+2
DO 50 I=1,N,12 (NL,TITLE)
CALL TVPAGE(NL,TITLE)
IF (I+11-N) 5,5,10
5 N5=12
GO TO 15
10 N5=N-I+1
15 DO 20 K=1,N5
20 ID(K) = I+K-1 (ID(K),K=1,N5)
WRITE(8,501)
NL = I + N5 - 1
IF (NA-1) 25,25,30 (T1(K),K=I,N1)
25 WRITE(8,504) (T1(K),K=I,N1)
GO TO 50
30 WRITE(8,502) (T2(K),K=I,N1)
WRITE(8,503) (T2(K),K=I,N1)
50 CONTINUE
RETURN

C
500 FORMAT (1H0)
501 FORMAT (/10H NODE NO. ,12I9.2)
502 FORMAT (12H NEW TEMPS ,12F9.2)
503 FORMAT (12H NEW - OLD ,12F9.2)
504 FORMAT (12H ORIG TEMPS ,12F9.2)
END

```


C

```

SUBROUTINE TVSHTR (NOHTRS,HTR,CASBTU,NOCONT,TOLD,NODCFH)
  IMPLICIT REAL*4 (A-H,O-Z)
  DIMENSION HTR(42), NOCONT(6), TOLD(315)
  CASBTU = 0.
  DO 25 K=1,NOHTRS
    LOK = 36+K
    IF (NOCONT(K)) 24,24,43
43  LOK1 = NOCONT(K)
    TEMP = TOLD(LOK1)
    IF (K-3) 45,45,50
45  LOK2 = 0
    GO TO 55
50  LOK2 = 18
55  IF (NODCFH) 3,3,60
60  IF (TEMP-HTR(2)) 65,65,70
65  HTR(LOK) = HTR(LOK2+1)
    CASBTU = CASBTU + HTR(LOK2+3)
    GO TO 25
70  NODCFH = 0
3  IF (TEMP - HTR(LOK2+4)) 5,5,15
5  HTR(LOK) = HTR(LOK2+9)
    CASBTU = CASBTU + HTR(LOK2+14)
    GO TO 25
15  DO 16 K1=5,8
    LOK3 = LOK2+K1
    IF (TEMP - HTR(LOK3)) 17,17,16
16  CONTINUE
    HTR(LOK) = HTR(LOK2+13)
    CASBTU = CASBTU + HTR(LOK2+18)
    GO TO 25
17  HTRL3 = HTR(LOK3) - HTR(LOK3 - 1)
    IF (ABS(HTRL3).LT.1E-06) HTRL3 = SIGN( 1E-06,HTRL3 )
    FRAC = (TEMP - HTR(LOK3-1)) / HTRL3
    HTR(LOK) = (HTR(LOK3+5) - HTR(LOK3+4)) * FRAC + HTR(LOK3+4)
    CASBTU = CASBTU + (HTR(LOK3+10) - HTR(LOK3+9)) * FRAC + HTR(LOK3+9)
    GO TO 25
24  HTR(LOK) = 0.
25  CONTINUE
    RETURN
  END

```

C

```

SUBROUTINE TVPAGE (NL,FNAME)
  IMPLICIT REAL*4 (A-H,O-Z)
  DIMENSION FNAME(20)
  IF (NL) 10,10,20
10  NPAGE = 0
    LINCNT = 75

```



```

20 LINCNT = LINCNT + NL
   IF (LINCNT - 56) 40,40,30
30 NPAGE = NPAGE + 1
   WRITE (8,50) FNAME,NPAGE
   LINCNT = NL
40 RETURN
50 FORMAT (1H1,20X,20A4,8X,9HPAGE NO. ,I3/)
   END
/*
//LKED.SYSLMOD DD DISP=SHR,DSNAME=MSS.S2323.LOADLIB
//LKED.SYSIN DD *
NAME TVCOUNT(R)
/*
//

```

MODIFIED NTU14 PROGRAM NTU14BC USED TO RUN ON BATCH SYSTEM

141

```

C      DO 20 I=1,3
C      20 L2(I) = 0

      L3{1} = 300
      L3{2} = 50
      L3{3} = 6
      L3{4} = 2
      L3{5} = 4
      L3{6} = 6

      FL4{1} = .05
      FL4{2} = .66667
      FL4{3} = .8
      FL4{4} = TINIT
      L4 = 12

CONSTANT TEMPERATURES
      SET2{1} = THOTIN(0,5)
      SET2{2} = TCLDIN(0,6)

READY FOR INPUT SET 4

NODE 1
      KCON{1,1} = 514
      KCON{1,2} = 1504
      KCON{1,3} = 1514
      KCON{1,4} = 2504
      KCON{1,5} = 3015
      COEF{1,5} = VALK1
      DO 50 I = 1,4
      50 COEF(1,I) = VALK3

      NODES 2 TO 50
      DO 75 I = 2,50
      J = I + 50
      K = 151 - I
      L = 150 + I
      M = 251 - I
      N = I - 1
      KCON(I,1) = 10*N + 5
      KCON(I,2) = 10*J + 4
      KCON(I,3) = 10*K + 4
      KCON(I,4) = 10*L + 4
      KCON(I,5) = 10*M + 4

```



```

    WRITE(2,911) FL4(1),FL4(2),L4,FL4(3),FL4(4)
911  FORMAT(F8.3,F8.5,I8,2F8.1)
912  WRITE(2,912) SET2(1),SET2(2)
    FORMAT(2F8.0)
C
    DO 200 I = 1,50
    WRITE(2,913) (KCON(I,J),J=1,5)
913  FORMAT(9I8)
914  WRITE(2,914) (COEF(I,J),J=1,5)
200  FORMAT(5F8.4)
    CONTINUE
C
    DO 250 I=51,250
    WRITE(2,913) KCON(I,1),KCON(I,2)
    WRITE(2,914) COEF(I,1),COEF(I,2)
250  CONTINUE
C
    7  CONTINUE
    STOP
    END
/*
//LKED:SYSLMOD DD DISP=SHR,DSNAME=MSS.S2323.LOAD
//LKED:SYSIN DD *
//NAME NTU14(R)
/*
//

```

APPENDIX H

NTU14BL LIBRARY BATCH PROGRAM

```
//OHN01 JOB (2323,0267) 'NTU14BL',CLASS=P
//**MAIN ORG=NPGVM1.2323P
//**FORMAT PR DDNAME=,DEST=LOCAL
//EXEC FORTVG,PROG=NTU14,LIB='MSS.S2323.LOAD'
//GO.TVSSIA DD DISP=(NEW,PASS) DSN=&TVSSIA,
//          UNIT=SYSDA,SPACE=(CYL(2,2)) BLKSIZE=6160)
//          DCB=(RECFM=FB,LRECL=80,TVSSIB,
//          DD DISP=(NEW,PASS) DSN=&TVSSIB,
//          UNIT=SYSDA,SPACE=(CYL(2,2))
//          DCB=(RECFM=FB,LRECL=80,TVSSIC,
//          DD DISP=(NEW,PASS) DSN=&TVSSIC,
//          UNIT=SYSDA,SPACE=(CYL(2,2)) BLKSIZE=6160)
//          DCB=(RECFM=FB,LRECL=80,TVSSID,
//          DD DISP=(NEW,PASS) DSN=&TVSSID,
//          UNIT=SYSDA,SPACE=(CYL(2,2)) BLKSIZE=6160)
//          DCB=(RECFM=FB,LRECL=80,TVSSIE,
//          DD DISP=(NEW,PASS) DSN=&TVSSIE,
//          UNIT=SYSDA,SPACE=(CYL(2,2)) BLKSIZE=6160)
//          DCB=(RECFM=FB,LRECL=80,TVSSIF,
//          DD DISP=(NEW,PASS) DSN=&TVSSIF,
//          UNIT=SYSDA,SPACE=(CYL(2,2)) BLKSIZE=6160)
//          DCB=(RECFM=FB,LRECL=80,TVSSIG,
//          DD DISP=(NEW,PASS) DSN=&TVSSIG,
//          UNIT=SYSDA,SPACE=(CYL(2,2)) BLKSIZE=6160)
//          DCB=(RECFM=FB,LRECL=80,TVSSIH,
//          DD DISP=(NEW,PASS) DSN=&TVSSIH,
//          UNIT=SYSDA,SPACE=(CYL(2,2)) BLKSIZE=6160)
//          DCB=(RECFM=FB,LRECL=80,TVSSII,
//          DD DISP=(NEW,PASS) DSN=&TVSSII,
//          UNIT=SYSDA,SPACE=(CYL(2,2)) BLKSIZE=6160)
//          DCB=(RECFM=FB,LRECL=80,TVSSIJ,
//          DD DISP=(NEW,PASS) DSN=&TVSSIJ,
//          UNIT=SYSDA,SPACE=(CYL(2,2)) BLKSIZE=6160)
//          DCB=(RECFM=FB,LRECL=80,TVSSIK,
//          DD DISP=(NEW,PASS) DSN=&TVSSIK,
//          DCB=(RECFM=FB,LRECL=80,TVSSIL,
//          DD *
//GO.FT01F001 DD 25.0 0.08333 15. 200. 100.
//          NTU=0.05 R=0.10 NTU14 25.0 0.41667 15. 200. 100.
//          NTU=0.25 R=0.10 NTU14 25.0 0.41667 15. 200. 100.
```

NTU=0.50	R=0.10	25.0	0.833333	15.	200.	100.
NTU14		NTU14	TVSSIC			
NTU=0.75	R=0.10	25.0	1.25000	15.	200.	100.
NTU14		NTU14	TVSSID			
NTU=1.00	R=0.10	25.0	1.66667	15.	200.	100.
NTU14		NTU14	TVSSIE			
NTU=1.25	R=0.10	25.0	2.083333	15.	200.	100.
NTU14		NTU14	TVSSIF			
NTU=1.50	R=0.10	25.0	2.50000	15.	200.	100.
NTU14		NTU14	TVSSIG			
NTU=2.00	R=0.10	25.0	3.333333	15.	200.	100.
NTU14		NTU14	TVSSIH			
NTU=2.50	R=0.10	25.0	4.16667	15.	200.	100.
NTU14		NTU14	TVSSII			
NTU=3.00	R=0.10	25.0	5.00000	15.	200.	100.
NTU14		NTU14	TVSSIJ			
NTU=3.25	R=0.10	25.0	5.41667	15.	200.	100.
NTU14		NTU14	TVSSIK			


```

//STEPA EXEC FORTVG, PROG=TVCOUNT, LIB='MSS.S2323.LOADLIB'
//GO.FT01F001 DD UNIT=SYSDA, SPACE={CYL,{1,1}}
//GO.FT02F001 DD UNIT=SYSDA, SPACE={CYL,{1,1}}
//GO.FT09F001 DD UNIT=SYSDA, SPACE={CYL,{1,1}}
//GO.FT10F001 DD UNIT=SYSDA, SPACE={CYL,{1,1}}
//GO.FT03F001 DD DUMMY
//GO.FT04F001 DD DISP=(OLD,DELETE), UNIT=SYSDA, DSN=&TVSSIA
//GO.FT08F001 DD SYSOUT=A, DCB=RECFM=FBA
//STEPB EXEC FORTVG, PROG=TVCOUNT, LIB='MSS.S2323.LOADLIB'
//GO.FT01F001 DD UNIT=SYSDA, SPACE={CYL,{1,1}}
//GO.FT02F001 DD UNIT=SYSDA, SPACE={CYL,{1,1}}
//GO.FT09F001 DD UNIT=SYSDA, SPACE={CYL,{1,1}}
//GO.FT10F001 DD UNIT=SYSDA, SPACE={CYL,{1,1}}
//GO.FT03F001 DD DUMMY
//GO.FT04F001 DD DISP=(OLD,DELETE), UNIT=SYSDA, DSN=&TVSSIB
//GO.FT08F001 DD SYSOUT=A, DCB=RECFM=FBA
//STPC EXEC FORTVG, PROG=TVCOUNT, LIB='MSS.S2323.LOADLIB'
//GO.FT01F001 DD UNIT=SYSDA, SPACE={CYL,{1,1}}
//GO.FT02F001 DD UNIT=SYSDA, SPACE={CYL,{1,1}}
//GO.FT09F001 DD UNIT=SYSDA, SPACE={CYL,{1,1}}
//GO.FT10F001 DD UNIT=SYSDA, SPACE={CYL,{1,1}}
//GO.FT03F001 DD DUMMY
//GO.FT04F001 DD DISP=(OLD,DELETE), UNIT=SYSDA, DSN=&TVSSIC
//GO.FT08F001 DD SYSOUT=A, DCB=RECFM=FBA
//STPD EXEC FORTVG, PROG=TVCOUNT, LIB='MSS.S2323.LOADLIB'
//GO.FT01F001 DD UNIT=SYSDA, SPACE={CYL,{1,1}}
//GO.FT02F001 DD UNIT=SYSDA, SPACE={CYL,{1,1}}
//GO.FT09F001 DD UNIT=SYSDA, SPACE={CYL,{1,1}}
//GO.FT10F001 DD UNIT=SYSDA, SPACE={CYL,{1,1}}

```



```

//GO.FT03F001 DD DUMMY
//GO.FT04F001 DD DISP=(OLD,DELETE),UNIT=SYSDA,DSN=&TVSSID
//GO.FT08F001 DD SYSOUT=A,DCB=RECFM=FBA
//STEPF EXEC FORTVG PROG=TVCOUNT,LIB=MSS.S2323.LOADLIB'
//GO.FT01F001 DD UNIT=SYSDA,SPACE={CYL,{1,1}}
//GO.FT02F001 DD UNIT=SYSDA,SPACE={CYL,{1,1}}
//GO.FT09F001 DD UNIT=SYSDA,SPACE={CYL,{1,1}}
//GO.FT10F001 DD UNIT=SYSDA,SPACE={CYL,{1,1}}
//GO.FT03F001 DD DUMMY
//GO.FT04F001 DD DISP=(OLD,DELETE),UNIT=SYSDA,DSN=&TVSSIE
//GO.FT08F001 DD SYSOUT=A,DCB=RECFM=FBA
//STEPF EXEC FORTVG PROG=TVCOUNT,LIB=MSS.S2323.LOADLIB'
//GO.FT01F001 DD UNIT=SYSDA,SPACE={CYL,{1,1}}
//GO.FT02F001 DD UNIT=SYSDA,SPACE={CYL,{1,1}}
//GO.FT09F001 DD UNIT=SYSDA,SPACE={CYL,{1,1}}
//GO.FT10F001 DD UNIT=SYSDA,SPACE={CYL,{1,1}}
//GO.FT03F001 DD DUMMY
//GO.FT04F001 DD DISP=(OLD,DELETE),UNIT=SYSDA,DSN=&TVSSIF
//GO.FT08F001 DD SYSOUT=A,DCB=RECFM=FBA
//STEPG EXEC FORTVG PROG=TVCOUNT,LIB=MSS.S2323.LOADLIB'
//GO.FT01F001 DD UNIT=SYSDA,SPACE={CYL,{1,1}}
//GO.FT02F001 DD UNIT=SYSDA,SPACE={CYL,{1,1}}
//GO.FT09F001 DD UNIT=SYSDA,SPACE={CYL,{1,1}}
//GO.FT10F001 DD UNIT=SYSDA,SPACE={CYL,{1,1}}
//GO.FT03F001 DD DUMMY
//GO.FT04F001 DD DISP=(OLD,DELETE),UNIT=SYSDA,DSN=&TVSSIG
//GO.FT08F001 DD SYSOUT=A,DCB=RECFM=FBA
//STEPH EXEC FORTVG PROG=TVCOUNT,LIB=MSS.S2323.LOADLIB'
//GO.FT01F001 DD UNIT=SYSDA,SPACE={CYL,{1,1}}
//GO.FT02F001 DD UNIT=SYSDA,SPACE={CYL,{1,1}}
//GO.FT09F001 DD UNIT=SYSDA,SPACE={CYL,{1,1}}
//GO.FT10F001 DD UNIT=SYSDA,SPACE={CYL,{1,1}}
//GO.FT03F001 DD DUMMY
//GO.FT04F001 DD DISP=(OLD,DELETE),UNIT=SYSDA,DSN=&TVSSIH
//GO.FT08F001 DD SYSOUT=A,DCB=RECFM=FBA
//STEPJ EXEC FORTVG PROG=TVCOUNT,LIB=MSS.S2323.LOADLIB'
//GO.FT01F001 DD UNIT=SYSDA,SPACE={CYL,{1,1}}
//GO.FT02F001 DD UNIT=SYSDA,SPACE={CYL,{1,1}}
//GO.FT09F001 DD UNIT=SYSDA,SPACE={CYL,{1,1}}
//GO.FT10F001 DD UNIT=SYSDA,SPACE={CYL,{1,1}}
//GO.FT03F001 DD DUMMY
//GO.FT04F001 DD DISP=(OLD,DELETE),UNIT=SYSDA,DSN=&TVSSII
//GO.FT08F001 DD SYSOUT=A,DCB=RECFM=FBA
//STEPK EXEC FORTVG PROG=TVCOUNT,LIB=MSS.S2323.LOADLIB'
//GO.FT01F001 DD UNIT=SYSDA,SPACE={CYL,{1,1}}
//GO.FT02F001 DD UNIT=SYSDA,SPACE={CYL,{1,1}}
//GO.FT09F001 DD UNIT=SYSDA,SPACE={CYL,{1,1}}
//GO.FT10F001 DD UNIT=SYSDA,SPACE={CYL,{1,1}}

```

```

//GO. FT03F001 DD DUMMY
//GO. FT04F001 DD DISP=(OLD,DELETE),UNIT=SYSDA,DSN=&TVSSIJ
//GO. FT08F001 DD SYSOUT=A,DCB=RECFM=FBA
//STEPK EXEC FORTVG,PROG=TVCOUNT,LIB=MSS.S2323.LOADLIB,
//GO. FT01F001 DD UNIT=SYSDA,SPACE=(CYL,{1,1})
//GO. FT02F001 DD UNIT=SYSDA,SPACE=(CYL,{1,1})
//GO. FT09F001 DD UNIT=SYSDA,SPACE=(CYL,{1,1})
//GO. FT10F001 DD UNIT=SYSDA,SPACE=(CYL,{1,1})
//GO. FT03F001 DD DUMMY
//GO. FT04F001 DD DISP=(OLD,DELETE),UNIT=SYSDA,DSN=&TVSSIK
//GO. FT08F001 DD SYSOUT=A,DCB=RECFM=FBA
//

```

APPENDIX I

MODIFIED NTU32C PROGRAM NTU32CC USED TO RUN ON BATCH SYSTEM

```

//OHHARE JOB (2323 0267) 'NTU32CC' CLASS=G
//**MAIN ORG=NPVGM1,2323P,SYSTEM=SY2,
//EXEC FORTVCL,PARM.LKED= LIST.MAP,
//FORT.SYSIN DD*
//THIS IS PROGRAM NTU32C

```

IT GENERATES AN INPUT FILE FOR THERMAL ANALYZER TO OBTAIN
1-3 EFFECTIVENESS-NTU RELATIONSHIP THAT IS NOT AVAILABLE IN
OPEN LITERATURE (2C MEANING ONE PARALLEL PASS AND TWO
COUNTERFLOW PASSES).

```

INTEGER O,P
DIMENSION COEF(200,5),KCON(200,5),L1(8),L2(3),L3(6),SET2(2),FL4(4)
1,CHOT(22,22),CCLD(22,22),U(22,22),SURFTO(22,22),THOTIN(22,22),
2TCLDIN(22,22),TITLE(22,22),FNAME(22,22)

```

CHARACTER *25 TITLE
CHARACTER *25 FNAME

```

DO 7 O=1,21,2
P=O+1
READ(1,900) CHOT(O,1),CCLD(O,2),U(O,3),SURFTO(O,4),THOTIN(O,5),TCL
1DIN(O,6)
900 FORMAT(2F10.0,F10.5,3F10.0)
918 READ(1,918) TITLE(P,1),FNAME(P,2)
918 FORMAT(2A25)

```

OPEN OUTPUT FILE

```
OPEN(2, FILE=FNAME(P, 2), FORM='FORMATTED')
```

```

VALK1 = CHOT(0,1)
VALK2 = CCLD(0,2)
VALK3 = U(0,3)*SURFT0(0,4)/150.
TINIT = 125.

```

FRONT END

$$\begin{matrix} L1 \\ L1 \\ DO \end{matrix} \begin{matrix} \{ \\ \{ \\ \} \end{matrix} \begin{matrix} 200 \\ 2 \\ 3,8 \end{matrix}$$

```

C      10 L1(I) = 0
      20 DO 20 I=1,3
      20 L2(I) = 0
C
      L3{1} = 300
      L3{2} = 50
      L3{3} = 6
      L3{4} = 2
      L3{5} = 4
      L3{6} = 6
C      FL4{1} = .05
      FL4{2} = .66667
      FL4{3} = .8
      FL4{4} = TINIT
      L4 = 12
C
C      CONSTANT TEMPERATURES
      SET2{1} = THOTIN(0,5)
      SET2{2} = TCLDIN(0,6)
C      READY FOR INPUT SET 4
C      NODE 1
C      KCON{1,1} = 1004
C      KCON{1,2} = 1014
C      KCON{1,3} = 2004
C      KCON{1,4} = 3015
C      COEF{1,4} = VALK1
      DO 50 I = 1,3
      50 COEF(1,I) = VALK3
C      NODES 2 TO 50
C      DO 75 I = 2,50
      J = 101 - I
      K = 100 + I
      L = 201 - I
      N = I - 1
      KCON{I,1} = 10*N + 5
      KCON{I,2} = 10*J + 4
      KCON{I,3} = 10*K + 4
      KCON{I,4} = 10*L + 4
      COEF{I,1} = VALK1
      DO 80 I = 2,4

```

```

      COEF(I,II) = VALK3
      80 CONTINUE
      75 CONTINUE
C
C
C   NODE 51
      KCON(51,1) = 3025
      KCON(51,2) = 504
      COEF(51,1) = VALK2
      COEF(51,2) = VALK3
C
C   NODES 52 TO 200
      DO 120 I = 52,200
      K = I - 1
      IF(I.GT.100) GO TO 122
      L = I - 50
      M = 2*L - 1
      J = I - M
      GO TO 135
122 IF(I.GT.150) GO TO 124
      J = I - 100
      GO TO 135
124 L = I - 150
      M = 2*L - 1
      J = I - M
      100 KCON(I,1) = 10*I + 4
      KCON(I,2) = 10*K + 5
      COEF(I,1) = VALK3
      COEF(I,2) = VALK2
120 CONTINUE
C
C   END OF DATA SETUP
C   NOW CREATE INPUT FOR ANALYZER
      WRITE(2,919) TITLE(P,1)
919 FORMAT(1X,A25)
      WRITE(2,908)(L1(I),I=1,8)
908 FORMAT(9I4)
      WRITE(2,908)(L2(I),I=1,3)
      WRITE(2,908)(L3(I),I=1,6)
      WRITE(2,911) FL4(1),FL4(2),L4,FL4(3),FL4(4)
911 FORMAT(F8.3,F8.5,I8,F8.5,F8.2)
912 FORMAT(2F8.0)
C
      DO 200 I = 1,50
      WRITE(2,913)(KCON(I,J),J=1,4)
913 FORMAT(9I8)

```

```

      WRITE(2,914)(COEF(I,J),J=1,4)
914  FORMAT(4F8.4)
200  CONTINUE
C
      DO 250 I=51,200
      WRITE(2,913) KCON(I,1),KCON(I,2)
      WRITE(2,914) COEF(I,1),COEF(I,2)
250  CONTINUE
C
      7  CONTINUE
      STOP
      END
/*
//LKED:SYSLMOD DD DISP=SHR,DSNAME=MSS.S2323.LOADLIB
//LKED:SYSIN DD *
//NAME COUNTER(R)
//

```

APPENDIX J

NTU32CL LIBRARY BATCH PROGRAM

```
//OH4CL JOB (2323, 0267) 'NTU32CL', CLASS=P
//**MAIN ORG=NPGVM1.2323P
//**FORMAT PR, DDNAME=, DEST=LOCAL
//EXEC FOR TVG, PROG=COUNT, LIB='MSS, S2323.LOADLIB'
//GO.TVSSIA
DD DISP=(NEW,PASS) DSN=&TVSSIA,
UNIT=SYSDA, SPACE=(CYL(2,2))
DCB=(RECFM=FB, LRECL=80, BLKSIZE=6160)
DD DISP=(NEW,PASS) DSN=&TVSSIB,
UNIT=SYSDA, SPACE=(CYL(2,2))
DCB=(RECFM=FB, LRECL=80, BLKSIZE=6160)
DD DISP=(NEW,PASS) DSN=&TVSSIC,
UNIT=SYSDA, SPACE=(CYL(2,2))
DCB=(RECFM=FB, LRECL=80, BLKSIZE=6160)
DD DISP=(NEW,PASS) DSN=&TVSSID,
UNIT=SYSDA, SPACE=(CYL(2,2))
DCB=(RECFM=FB, LRECL=80, BLKSIZE=6160)
DD DISP=(NEW,PASS) DSN=&TVSSIE,
UNIT=SYSDA, SPACE=(CYL(2,2))
DCB=(RECFM=FB, LRECL=80, BLKSIZE=6160)
DD DISP=(NEW,PASS) DSN=&TVSSIF,
UNIT=SYSDA, SPACE=(CYL(2,2))
DCB=(RECFM=FB, LRECL=80, BLKSIZE=6160)
DD DISP=(NEW,PASS) DSN=&TVSSIG,
UNIT=SYSDA, SPACE=(CYL(2,2))
DCB=(RECFM=FB, LRECL=80, BLKSIZE=6160)
DD DISP=(NEW,PASS) DSN=&TVSSIH,
UNIT=SYSDA, SPACE=(CYL(2,2))
DCB=(RECFM=FB, LRECL=80, BLKSIZE=6160)
DD DISP=(NEW,PASS) DSN=&TVSSII,
UNIT=SYSDA, SPACE=(CYL(2,2))
DCB=(RECFM=FB, LRECL=80, BLKSIZE=6160)
DD DISP=(NEW,PASS) DSN=&TVSSIJ,
UNIT=SYSDA, SPACE=(CYL(2,2))
DCB=(RECFM=FB, LRECL=80, BLKSIZE=6160)
DD DISP=(NEW,PASS) DSN=&TVSSIK,
UNIT=SYSDA, SPACE=(CYL(2,2))
DCB=(RECFM=FB, LRECL=80, BLKSIZE=6160)
//GO.FT01F001 DD*
100.0 0.33333 15. 200. 100.
NTU=0.05 R=0.40 COUNTER TVSSIA 100.
250. 100.0 1.66667 15. 200. 100.
NTU=0.25 R=0.40 COUNTER TVSSIB
```


NTU=0.50	R=0.40	100.0	3.33333						
	COUNTER			15.	200.	100.			
	TVSSIC								
NTU=0.75	R=0.40	100.0	5.00000	15.	200.	100.			
	COUNTER								
	TVSSID								
NTU=1.00	R=0.40	100.0	6.66667	15.	200.	100.			
	COUNTER								
	TVSSIE								
NTU=1.25	R=0.40	100.0	8.33333	15.	200.	100.			
	COUNTER								
	TVSSIF								
NTU=1.50	R=0.40	100.0	10.00000	15.	200.	100.			
	COUNTER								
	TVSSIG								
NTU=2.00	R=0.40	100.0	13.33333	15.	200.	100.			
	COUNTER								
	TVSSIH								
NTU=2.50	R=0.40	100.0	16.66666	15.	200.	100.			
	COUNTER								
	TVSSII								
NTU=3.00	R=0.40	100.0	20.00000	15.	200.	100.			
	COUNTER								
	TVSSIJ								
NTU=3.25	R=0.40	100.0	21.66666	15.	200.	100.			
	COUNTER								
	TVSSIK								

```

/*
// STEPA EXEC FORTVG, PROG=TVCOUNT, LIB='MSS, S2323.LOADLIB'
//GO.FT01F001 DD UNIT=SYSDA, SPACE={CYL, {1,1}}
//GO.FT02F001 DD UNIT=SYSDA, SPACE={CYL, {1,1}}
//GO.FT09F001 DD UNIT=SYSDA, SPACE={CYL, {1,1}}
//GO.FT10F001 DD UNIT=SYSDA, SPACE={CYL, {1,1}}
//GO.FT03F001 DD DUMMY
//GO.FT04F001 DD DISP=(OLD, DELETE), UNIT=SYSDA, DSN=&TVSSIA
//GO.FT08F001 DD SYSOUT=A, DCB=RECFM=FBA
// STEPB EXEC FORTVG, PROG=TVCOUNT, LIB='MSS, S2323.LOADLIB'
//GO.FT01F001 DD UNIT=SYSDA, SPACE={CYL, {1,1}}
//GO.FT02F001 DD UNIT=SYSDA, SPACE={CYL, {1,1}}
//GO.FT09F001 DD UNIT=SYSDA, SPACE={CYL, {1,1}}
//GO.FT10F001 DD UNIT=SYSDA, SPACE={CYL, {1,1}}
//GO.FT03F001 DD DUMMY
//GO.FT04F001 DD DISP=(OLD, DELETE), UNIT=SYSDA, DSN=&TVSSIB
//GO.FT08F001 DD SYSOUT=A, DCB=RECFM=FBA
// STEPC EXEC FORTVG, PROG=TVCOUNT, LIB='MSS, S2323.LOADLIB'
//GO.FT01F001 DD UNIT=SYSDA, SPACE={CYL, {1,1}}
//GO.FT02F001 DD UNIT=SYSDA, SPACE={CYL, {1,1}}
//GO.FT09F001 DD UNIT=SYSDA, SPACE={CYL, {1,1}}
//GO.FT10F001 DD UNIT=SYSDA, SPACE={CYL, {1,1}}
//GO.FT03F001 DD DUMMY
//GO.FT04F001 DD DISP=(OLD, DELETE), UNIT=SYSDA, DSN=&TVSSIC
//GO.FT08F001 DD SYSOUT=A, DCB=RECFM=FBA
// STEPD EXEC FORTVG, PROG=TVCOUNT, LIB='MSS, S2323.LOADLIB'
//GO.FT01F001 DD UNIT=SYSDA, SPACE={CYL, {1,1}}
//GO.FT02F001 DD UNIT=SYSDA, SPACE={CYL, {1,1}}
//GO.FT09F001 DD UNIT=SYSDA, SPACE={CYL, {1,1}}
//GO.FT10F001 DD UNIT=SYSDA, SPACE={CYL, {1,1}}

```

```

//GO.FT03F001 DD DUMMY
//GO.FT04F001 DD DISP=(OLD,DELETE),UNIT=SYSDA,DSN=&TVSSID
//GO.FT08F001 DD SYSOUT=A,DCB=RECFM=FBA
//STEPE EXEC FORTVG,PROG=TVCOUNT,LIB=MSS,S2323.LOADLIB'
//GO.FT01F001 DD UNIT=SYSDA,SPACE=(CYL,1,1)}
//GO.FT02F001 DD UNIT=SYSDA,SPACE=(CYL,1,1)}
//GO.FT09F001 DD UNIT=SYSDA,SPACE=(CYL,1,1)}
//GO.FT10F001 DD UNIT=SYSDA,SPACE=(CYL,1,1)}
//GO.FT03F001 DD DUMMY
//GO.FT04F001 DD DISP=(OLD,DELETE),UNIT=SYSDA,DSN=&TVSSIE
//GO.FT08F001 DD SYSOUT=A,DCB=RECFM=FBA
//STEPF EXEC FORTVG,PROG=TVCOUNT,LIB=MSS,S2323.LOADLIB'
//GO.FT01F001 DD UNIT=SYSDA,SPACE=(CYL,1,1)}
//GO.FT02F001 DD UNIT=SYSDA,SPACE=(CYL,1,1)}
//GO.FT09F001 DD UNIT=SYSDA,SPACE=(CYL,1,1)}
//GO.FT10F001 DD UNIT=SYSDA,SPACE=(CYL,1,1)}
//GO.FT03F001 DD DUMMY
//GO.FT04F001 DD DISP=(OLD,DELETE),UNIT=SYSDA,DSN=&TVSSIF
//GO.FT08F001 DD SYSOUT=A,DCB=RECFM=FBA
//STEPG EXEC FORTVG,PROG=TVCOUNT,LIB=MSS,S2323.LOADLIB'
//GO.FT01F001 DD UNIT=SYSDA,SPACE=(CYL,1,1)}
//GO.FT02F001 DD UNIT=SYSDA,SPACE=(CYL,1,1)}
//GO.FT09F001 DD UNIT=SYSDA,SPACE=(CYL,1,1)}
//GO.FT10F001 DD UNIT=SYSDA,SPACE=(CYL,1,1)}
//GO.FT03F001 DD DUMMY
//GO.FT04F001 DD DISP=(OLD,DELETE),UNIT=SYSDA,DSN=&TVSSIG
//GO.FT08F001 DD SYSOUT=A,DCB=RECFM=FBA
//STEPH EXEC FORTVG,PROG=TVCOUNT,LIB=MSS,S2323.LOADLIB'
//GO.FT01F001 DD UNIT=SYSDA,SPACE=(CYL,1,1)}
//GO.FT02F001 DD UNIT=SYSDA,SPACE=(CYL,1,1)}
//GO.FT09F001 DD UNIT=SYSDA,SPACE=(CYL,1,1)}
//GO.FT10F001 DD UNIT=SYSDA,SPACE=(CYL,1,1)}
//GO.FT03F001 DD DUMMY
//GO.FT04F001 DD DISP=(OLD,DELETE),UNIT=SYSDA,DSN=&TVSSIH
//GO.FT08F001 DD SYSOUT=A,DCB=RECFM=FBA
//STEPJ EXEC FORTVG,PROG=TVCOUNT,LIB=MSS,S2323.LOADLIB'
//GO.FT01F001 DD UNIT=SYSDA,SPACE=(CYL,1,1)}
//GO.FT02F001 DD UNIT=SYSDA,SPACE=(CYL,1,1)}
//GO.FT09F001 DD UNIT=SYSDA,SPACE=(CYL,1,1)}
//GO.FT10F001 DD UNIT=SYSDA,SPACE=(CYL,1,1)}
//GO.FT03F001 DD DUMMY
//GO.FT04F001 DD DISP=(OLD,DELETE),UNIT=SYSDA,DSN=&TVSSII
//GO.FT08F001 DD SYSOUT=A,DCB=RECFM=FBA
//STEPK EXEC FORTVG,PROG=TVCOUNT,LIB=MSS,S2323.LOADLIB'
//GO.FT01F001 DD UNIT=SYSDA,SPACE=(CYL,1,1)}
//GO.FT02F001 DD UNIT=SYSDA,SPACE=(CYL,1,1)}
//GO.FT09F001 DD UNIT=SYSDA,SPACE=(CYL,1,1)}
//GO.FT10F001 DD UNIT=SYSDA,SPACE=(CYL,1,1)}

```

```

//GO.FT03F001 DD DUMMY
//GO.FT04F001 DD DISP=(OLD,DELETE),UNIT=SYSDA,DSN=&TVSSIJ
//GO.FT08F001 DD SYSOUT=A,DCB=RECFM=FBA
//STEPK EXEC FORTVG,PROG=TVCOUNT,LIB=MSS,S2323.LOADLIB'
//GO.FT01F001 DD UNIT=SYSDA,SPACE={CYL,{1,1}}
//GO.FT02F001 DD UNIT=SYSDA,SPACE={CYL,{1,1}}
//GO.FT09F001 DD UNIT=SYSDA,SPACE={CYL,{1,1}}
//GO.FT10F001 DD UNIT=SYSDA,SPACE={CYL,{1,1}}
//GO.FT03F001 DD DUMMY
//GO.FT04F001 DD DISP=(OLD,DELETE),UNIT=SYSDA,DSN=&TVSSIK
//GO.FT08F001 DD SYSOUT=A,DCB=RECFM=FBA
//

```

APPENDIX K

MODIFIED NTU32P PROGRAM NTU32PC USED TO RUN ON BATCH SYSTEM

```
//OH32PC JOB (2323 0267), 'NTU32PC', CLASS=G
// *MAIN ORG=NPVMI.2323P, SYSTEM=SY2,
// EXEC FORTVCL, PARM.LKED= 'LIST, MAP',
// FORT.SYSIN DD
// THIS IS PROGRAM NTU32P
CCCCCCCC
IT GENERATES AN INPUT FILE FOR THERMAL ANALYZER TO OBTAIN
1-3 EFFECTIVENESS-NTU RELATIONSHIP THAT IS NOT AVAILABLE IN
OPEN LITERATURE (2P MEANING TWO PARALLEL PASSES AND ONE
COUNTERFLOW PASS).
CCCCCCCC
INTEGER O, P
DIMENSION COEF(200,5) KCON(200,5), L1(8), L2(3), L3(6), SET2(2), FL4(4)
1 CHOT(22,22), CCLD(22,22), U(22,22), SURFTO(22,22), THOTIN(22,22),
2 TCLDIN(22,22), TITLE(22,22), FNAME(22,22)
CCCCCCCC
CHARACTER *25 TITLE
CHARACTER *25 FNAME
C
DO 7 O=1,21,2
P=O+1
READ(1,900) CHOT(O,1), CCLD(O,2), U(O,3), SURFTO(O,4), THOTIN(O,5), TCL
1 DIN(O,6)
900 FORMAT(2F10.0, F10.5, 3F10.0)
918 READ(1,918) TITLE(P,1), FNAME(P,2)
918 FORMAT(2A25)
CCCCCCCC
OPEN OUTPUT FILE
OPEN(2, FILE=FNAME(P,2), FORM='FORMATTED')
C
VALK1 = CHOT(O,1)
VALK2 = CCLD(O,2)
VALK3 = U(O,3)*SURFTO(O,4)/150.
TINIT = 125.
CCCCCCCC
FRONT END
L1(1) = 200
L1(2) = 2
DO 10 I=3,8
```

```

C      10 L1(I) = 0
C      DO 20 I=1,3
C      20 L2(I) = 0
C
C      L3{1} = 300
C      L3{2} = 50
C      L3{3} = 6
C      L3{4} = 2
C      L3{5} = 4
C      L3{6} = 6
C
C      FL4{1} = .05
C      FL4{2} = .66667
C      FL4{3} = .8
C      FL4{4} = TINIT
C      L4 = 12
C
C      CONSTANT TEMPERATURES
C      SET2{1} = THOTIN(0,5)
C      SET2{2} = TCOLDIN(0,6)
C
C      READY FOR INPUT SET 4
C      NODE 1
C
C      KCON{1,1} = 514
C      KCON{1,2} = 1504
C      KCON{1,3} = 1514
C      KCON{1,4} = 3015
C      COEF{1,4} = VALK1
C      DO 50 I=1,3
C      50 COEF(I,I) = VALK3
C
C      NODES 2 TO 50
C
C      DO 75 I = 2,50
C      J = I + 50
C      K = 151 - I
C      L = 150 + I
C      N = I - 1
C      KCON{I,1} = 10*N + 5
C      KCON{I,2} = 10*J + 4
C      KCON{I,3} = 10*K + 4
C      KCON{I,4} = 10*L + 4
C      COEF{I,1} = VALK1
C      DO 80 I,II
C      80

```

```

      COEF(I,II) = VALK3
      80 CONTINUE
      75 CONTINUE
C
C
C   NODE 51
      KCON(51,1) = 3025
      KCON(51,2) = 14
      COEF(51,1) = VALK2
      COEF(51,2) = VALK3
C
C   NODES 52 TO 200
      DO 120 I = 52,200
      K = I - 1
      IF(I.GT.100) GO TO 122
      J = I - 50
      GO TO 135
122 IF(I.GT.150) GO TO 124
      L = I - 100
      M = 2*L - 1
      N = M + 50
      J = I - N
      GO TO 135
124 J = I - 150
135 KCON(I,1) = 10*K + 4
      KCON(I,2) = 10*K + 5
      COEF(I,1) = VALK3
      COEF(I,2) = VALK2
120 CONTINUE
C
C   END OF DATA SETUP
C   NOW CREATE INPUT FOR ANALYZER
      WRITE(2,919) TITLE(P,1)
919 FORMAT(1X,A25)
      WRITE(2,908)(L1(I),I=1,8)
908 FORMAT(9I4)
      WRITE(2,908)(L2(I),I=1,3)
      WRITE(2,908)(L3(I),I=1,6)
      WRITE(2,911) FL4(1),FL4(2),L4,FL4(3),FL4(4)
911 FORMAT(F8.3,F8.5,I8,F8.5,F8.2)
912 WRITE(2,912) SET2(1),SET2(2)
      FORMAT(2F8.0)
C
      DO 200 I = 1,50
      WRITE(2,913)(KCON(I,J),J=1,4)
913 FORMAT(9I8)
      WRITE(2,914)(COEF(I,J),J=1,4)

```

```

914 FORMAT(4F8.4)
200 CONTINUE
C
DO 250 I=51,200
WRITE(2,913) KCON(I,1),KCON(I,2)
WRITE(2,914) COEF(I,1),COEF(I,2)
250 CONTINUE
C 7 CONTINUE
STOP
END
/*
//LKED.SYSLMOD DD DISP=SHR,DSNAME=MSS.S2323.LOADLIB
//LKED.SYSIN DD
NAME PARALLEL(R)
/*
//

```


APPENDIX L

NTU32PL LIBRARY BATCH PROGRAM

```

//OH2PL JOB (2323,0267) 'NTU32PL',CLASS=P
//*MAIN ORG=NPGVM1.2323P
//*FORMAT PR DDNAME=,DEST=LOCAL
//EXEC FORTV,PROG=PARALLEL,LIB='MSS.S2323.LOADLIB'
//GO.TVSSIL
//DD DISP=(NEW,PASS) DSN=&TVSSIL,
//DCB=(RECFM=FB,LRECL=80,BLKSIZE=6160)
//DD DISP=(NEW,PASS) DSN=&TVSSIM,
//UNIT=SYSDA,SPACE=(CYL(2,2))
//DCB=(RECFM=FB,LRECL=80,BLKSIZE=6160)
//DD DISP=(NEW,PASS) DSN=&TVSSIN,
//UNIT=SYSDA,SPACE=(CYL(2,2))
//DCB=(RECFM=FB,LRECL=80,BLKSIZE=6160)
//DD DISP=(NEW,PASS) DSN=&TVSSIO,
//UNIT=SYSDA,SPACE=(CYL(2,2))
//DCB=(RECFM=FB,LRECL=80,BLKSIZE=6160)
//DD DISP=(NEW,PASS) DSN=&TVSSIP,
//UNIT=SYSDA,SPACE=(CYL(2,2))
//DCB=(RECFM=FB,LRECL=80,BLKSIZE=6160)
//DD DISP=(NEW,PASS) DSN=&TVSSIQ,
//UNIT=SYSDA,SPACE=(CYL(2,2))
//DCB=(RECFM=FB,LRECL=80,BLKSIZE=6160)
//DD DISP=(NEW,PASS) DSN=&TVSSIR,
//UNIT=SYSDA,SPACE=(CYL(2,2))
//DCB=(RECFM=FB,LRECL=80,BLKSIZE=6160)
//DD DISP=(NEW,PASS) DSN=&TVSSIS,
//UNIT=SYSDA,SPACE=(CYL(2,2))
//DCB=(RECFM=FB,LRECL=80,BLKSIZE=6160)
//DD DISP=(NEW,PASS) DSN=&TVSSIT,
//UNIT=SYSDA,SPACE=(CYL(2,2))
//DCB=(RECFM=FB,LRECL=80,BLKSIZE=6160)
//DD DISP=(NEW,PASS) DSN=&TVSSIU,
//UNIT=SYSDA,SPACE=(CYL(2,2))
//DCB=(RECFM=FB,LRECL=80,BLKSIZE=6160)
//DD DISP=(NEW,PASS) DSN=&TVSSIV,
//UNIT=SYSDA,SPACE=(CYL(2,2))
//DCB=(RECFM=FB,LRECL=80,BLKSIZE=6160)
//GO.FT01F001 DD*
//150.0 0.50000 15. 200. 100.
NTU=0.05 R=0.60 COUNTER TVSSIA
250
//150.0 2.50000 15. 200. 100.
NTU=0.25 R=0.60 COUNTER TVSSIB
250

```

NTU=0.50	R=0.60	150.0	5.00000	15.	200.	100.
		COUNTER	TVSSIC			
NTU=0.250	R=0.60	150.0	7.50000	15.	200.	100.
		COUNTER	TVSSID			
NTU=0.250	R=0.60	150.0	10.00000	15.	200.	100.
		COUNTER	TVSSIE			
NTU=1.00	R=0.60	150.0	12.50000	15.	200.	100.
		COUNTER	TVSSIF			
NTU=1.250	R=0.60	150.0	15.00000	15.	200.	100.
		COUNTER	TVSSIG			
NTU=1.50	R=0.60	150.0	20.00000	15.	200.	100.
		COUNTER	TVSSIH			
NTU=2.00	R=0.60	150.0	25.00000	15.	200.	100.
		COUNTER	TVSSII			
NTU=2.50	R=0.60	150.0	30.00000	15.	200.	100.
		COUNTER	TVSSIJ			
NTU=3.00	R=0.60	150.0	32.50000	15.	200.	100.
		COUNTER	TVSSIK			
NTU=3.25	R=0.60					
/*						
//STEPL EXEC FORTVG, PROG=TVCOUNT, LIB='MSS, S2323.LOADLIB'						
//GO.	FT01F001	DD	UNIT=SYSDA, SPACE={CYL, {1,1}}			
//GO.	FT02F001	DD	UNIT=SYSDA, SPACE={CYL, {1,1}}			
//GO.	FT09F001	DD	UNIT=SYSDA, SPACE={CYL, {1,1}}			
//GO.	FT10F001	DD	UNIT=SYSDA, SPACE={CYL, {1,1}}			
//GO.	FT03F001	DD	DUMMY			
//GO.	FT04F001	DD	DISP=(OLD, DELETE), UNIT=SYSDA, DSN=&TVSSIL			
//GO.	FT08F001	DD	SYSOUT=A, DCB=RECFM=FBA			
//STEPM EXEC FORTVG, PROG=TVCOUNT, LIB='MSS, S2323.LOADLIB'						
//GO.	FT01F001	DD	UNIT=SYSDA, SPACE={CYL, {1,1}}			
//GO.	FT02F001	DD	UNIT=SYSDA, SPACE={CYL, {1,1}}			
//GO.	FT09F001	DD	UNIT=SYSDA, SPACE={CYL, {1,1}}			
//GO.	FT10F001	DD	UNIT=SYSDA, SPACE={CYL, {1,1}}			
//GO.	FT03F001	DD	DUMMY			
//GO.	FT04F001	DD	DISP=(OLD, DELETE), UNIT=SYSDA, DSN=&TVSSIM			
//GO.	FT08F001	DD	SYSOUT=A, DCB=RECFM=FBA			
//STEPN EXEC FORTVG, PROG=TVCOUNT, LIB='MSS, S2323.LOADLIB'						
//GO.	FT01F001	DD	UNIT=SYSDA, SPACE={CYL, {1,1}}			
//GO.	FT02F001	DD	UNIT=SYSDA, SPACE={CYL, {1,1}}			
//GO.	FT09F001	DD	UNIT=SYSDA, SPACE={CYL, {1,1}}			
//GO.	FT10F001	DD	UNIT=SYSDA, SPACE={CYL, {1,1}}			
//GO.	FT03F001	DD	DUMMY			
//GO.	FT04F001	DD	DISP=(OLD, DELETE), UNIT=SYSDA, DSN=&TVSSIN			
//GO.	FT08F001	DD	SYSOUT=A, DCB=RECFM=FBA			
//STEPQ EXEC FORTVG, PROG=TVCOUNT, LIB='MSS, S2323.LOADLIB'						
//GO.	FT01F001	DD	UNIT=SYSDA, SPACE={CYL, {1,1}}			
//GO.	FT02F001	DD	UNIT=SYSDA, SPACE={CYL, {1,1}}			
//GO.	FT09F001	DD	UNIT=SYSDA, SPACE={CYL, {1,1}}			
//GO.	FT10F001	DD	UNIT=SYSDA, SPACE={CYL, {1,1}}			

```

//GO. FT03F001 DD DUMMY
//GO. FT04F001 DD DISP=(OLD,DELETE),UNIT=SYSDA,DSN=&TVSSIO
//GO. FT08F001 DD SYSOUT=A,DCB=RECFM=FBA
//STEPP EXEC FORTVG,PROG=TVCOUNT,LIB=MSS:S2323.LOADLIB'
//GO. FT01F001 DD UNIT=SYSDA,SPACE=(CYL,{1,1})
//GO. FT02F001 DD UNIT=SYSDA,SPACE=(CYL,{1,1})
//GO. FT09F001 DD UNIT=SYSDA,SPACE=(CYL,{1,1})
//GO. FT10F001 DD UNIT=SYSDA,SPACE=(CYL,{1,1})
//GO. FT03F001 DD DUMMY
//GO. FT04F001 DD DISP=(OLD,DELETE),UNIT=SYSDA,DSN=&TVSSIP
//GO. FT08F001 DD SYSOUT=A,DCB=RECFM=FBA
//STEPQ EXEC FORTVG,PROG=TVCOUNT,LIB=MSS:S2323.LOADLIB'
//GO. FT01F001 DD UNIT=SYSDA,SPACE=(CYL,{1,1})
//GO. FT02F001 DD UNIT=SYSDA,SPACE=(CYL,{1,1})
//GO. FT09F001 DD UNIT=SYSDA,SPACE=(CYL,{1,1})
//GO. FT10F001 DD UNIT=SYSDA,SPACE=(CYL,{1,1})
//GO. FT03F001 DD DUMMY
//GO. FT04F001 DD DISP=(OLD,DELETE),UNIT=SYSDA,DSN=&TVSSIQ
//GO. FT08F001 DD SYSOUT=A,DCB=RECFM=FBA
//STEPR EXEC FORTVG,PROG=TVCOUNT,LIB=MSS:S2323.LOADLIB'
//GO. FT01F001 DD UNIT=SYSDA,SPACE=(CYL,{1,1})
//GO. FT02F001 DD UNIT=SYSDA,SPACE=(CYL,{1,1})
//GO. FT09F001 DD UNIT=SYSDA,SPACE=(CYL,{1,1})
//GO. FT10F001 DD UNIT=SYSDA,SPACE=(CYL,{1,1})
//GO. FT03F001 DD DUMMY
//GO. FT04F001 DD DISP=(OLD,DELETE),UNIT=SYSDA,DSN=&TVSSIR
//GO. FT08F001 DD SYSOUT=A,DCB=RECFM=FBA
//STEPS EXEC FORTVG,PROG=TVCOUNT,LIB=MSS:S2323.LOADLIB'
//GO. FT01F001 DD UNIT=SYSDA,SPACE=(CYL,{1,1})
//GO. FT02F001 DD UNIT=SYSDA,SPACE=(CYL,{1,1})
//GO. FT09F001 DD UNIT=SYSDA,SPACE=(CYL,{1,1})
//GO. FT10F001 DD UNIT=SYSDA,SPACE=(CYL,{1,1})
//GO. FT03F001 DD DUMMY
//GO. FT04F001 DD DISP=(OLD,DELETE),UNIT=SYSDA,DSN=&TVSSIS
//GO. FT08F001 DD SYSOUT=A,DCB=RECFM=FBA
//STEPT EXEC FORTVG,PROG=TVCOUNT,LIB=MSS:S2323.LOADLIB'
//GO. FT01F001 DD UNIT=SYSDA,SPACE=(CYL,{1,1})
//GO. FT02F001 DD UNIT=SYSDA,SPACE=(CYL,{1,1})
//GO. FT09F001 DD UNIT=SYSDA,SPACE=(CYL,{1,1})
//GO. FT10F001 DD UNIT=SYSDA,SPACE=(CYL,{1,1})
//GO. FT03F001 DD DUMMY
//GO. FT04F001 DD DISP=(OLD,DELETE),UNIT=SYSDA,DSN=&TVSSIT
//GO. FT08F001 DD SYSOUT=A,DCB=RECFM=FBA
//STEPU EXEC FORTVG,PROG=TVCOUNT,LIB=MSS:S2323.LOADLIB'
//GO. FT01F001 DD UNIT=SYSDA,SPACE=(CYL,{1,1})
//GO. FT02F001 DD UNIT=SYSDA,SPACE=(CYL,{1,1})
//GO. FT09F001 DD UNIT=SYSDA,SPACE=(CYL,{1,1})
//GO. FT10F001 DD UNIT=SYSDA,SPACE=(CYL,{1,1})

```

```

//GO.FT03F001 DD DUMMY
//GO.FT04F001 DD DISP=(OLD,DELETE),UNIT=SYSDA,DSN=&TVSSIU
//GO.FT08F001 DD SYSOUT=A,DCB=RECFM=FBA
//STEPV EXEC FORTVG,PROG=TVCOUNT,LIB='MSS.S2323.LOADLIB'
//GO.FT01F001 DD UNIT=SYSDA,SPACE={CYL,{1,1}}
//GO.FT02F001 DD UNIT=SYSDA,SPACE={CYL,{1,1}}
//GO.FT09F001 DD UNIT=SYSDA,SPACE={CYL,{1,1}}
//GO.FT10F001 DD UNIT=SYSDA,SPACE={CYL,{1,1}}
//GO.FT03F001 DD DUMMY
//GO.FT04F001 DD DISP=(OLD,DELETE),UNIT=SYSDA,DSN=&TVSSIV
//GO.FT08F001 DD SYSOUT=A,DCB=RECFM=FBA
//

```

APPENDIX M

1-3:2C EFFECTIVENESS VS. N_{tu} GRAPHS AT VARIOUS R VALUES

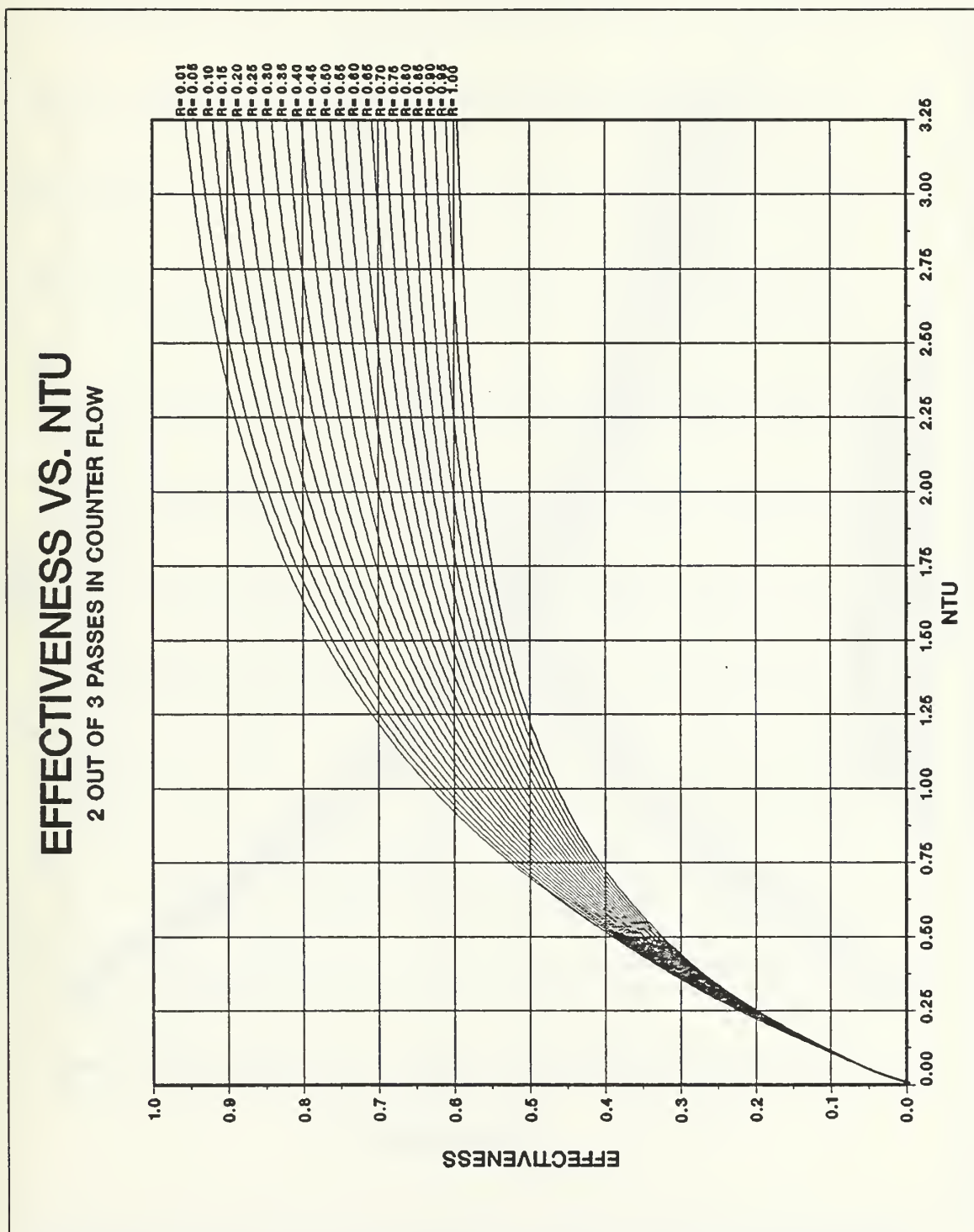


Figure M.1 1-3:2C Effectiveness vs. N_{tu} over Range of R from 0.01 to 1.0

EFFECTIVENESS VS. NTU **2 OUT OF 3 PASSES IN COUNTER FLOW** **FOR R VARYING BY .01 FROM .01 TO 0.1**

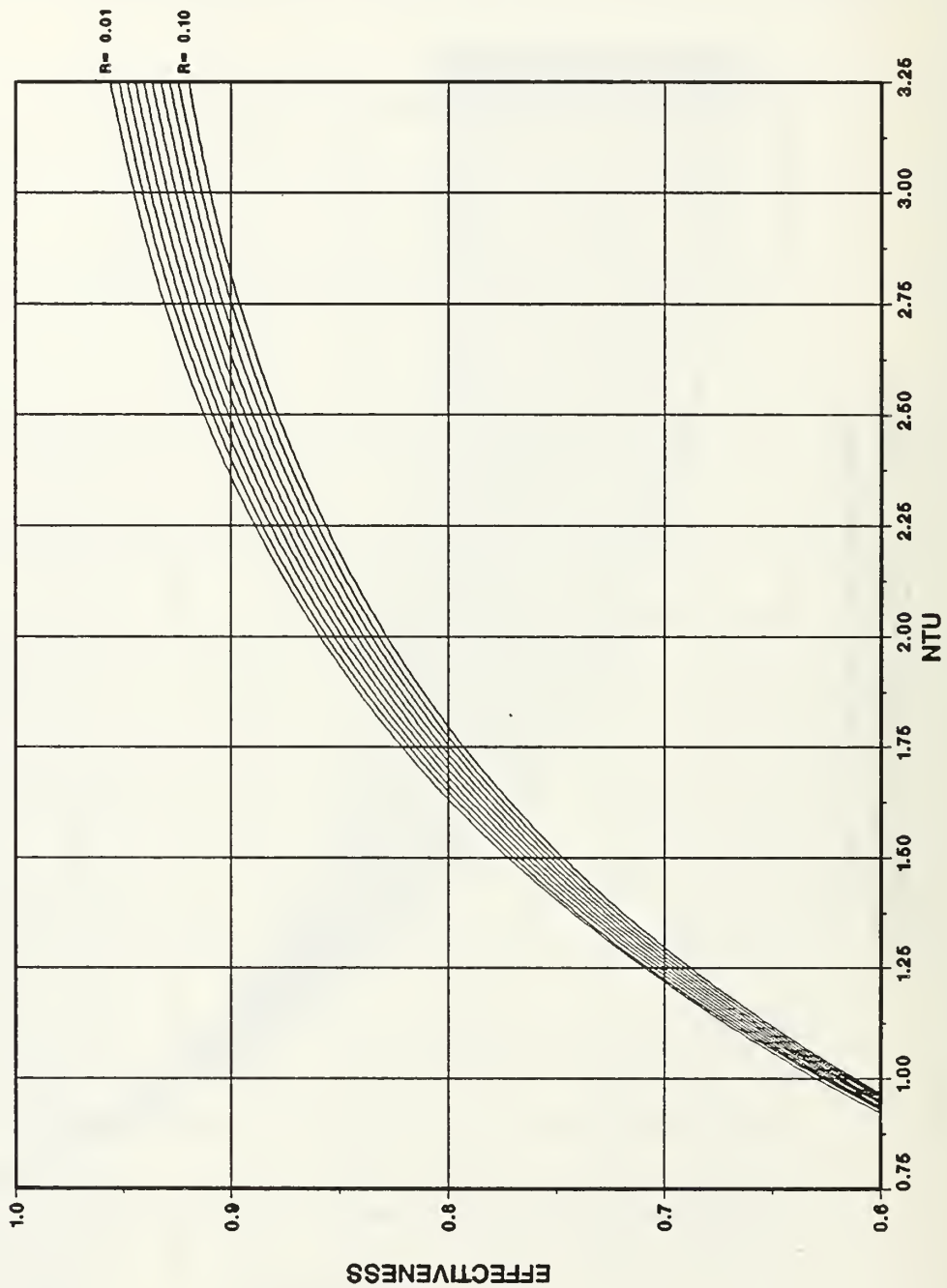


Figure M.2 1-3:2C Effectiveness vs. N_{tu} over Range of R from 0.01 to 0.10

EFFECTIVENESS VS. NTU 2 OUT OF 3 PASSES IN COUNTER FLOW FOR R VARYING BY .01 FROM .11 TO 0.2

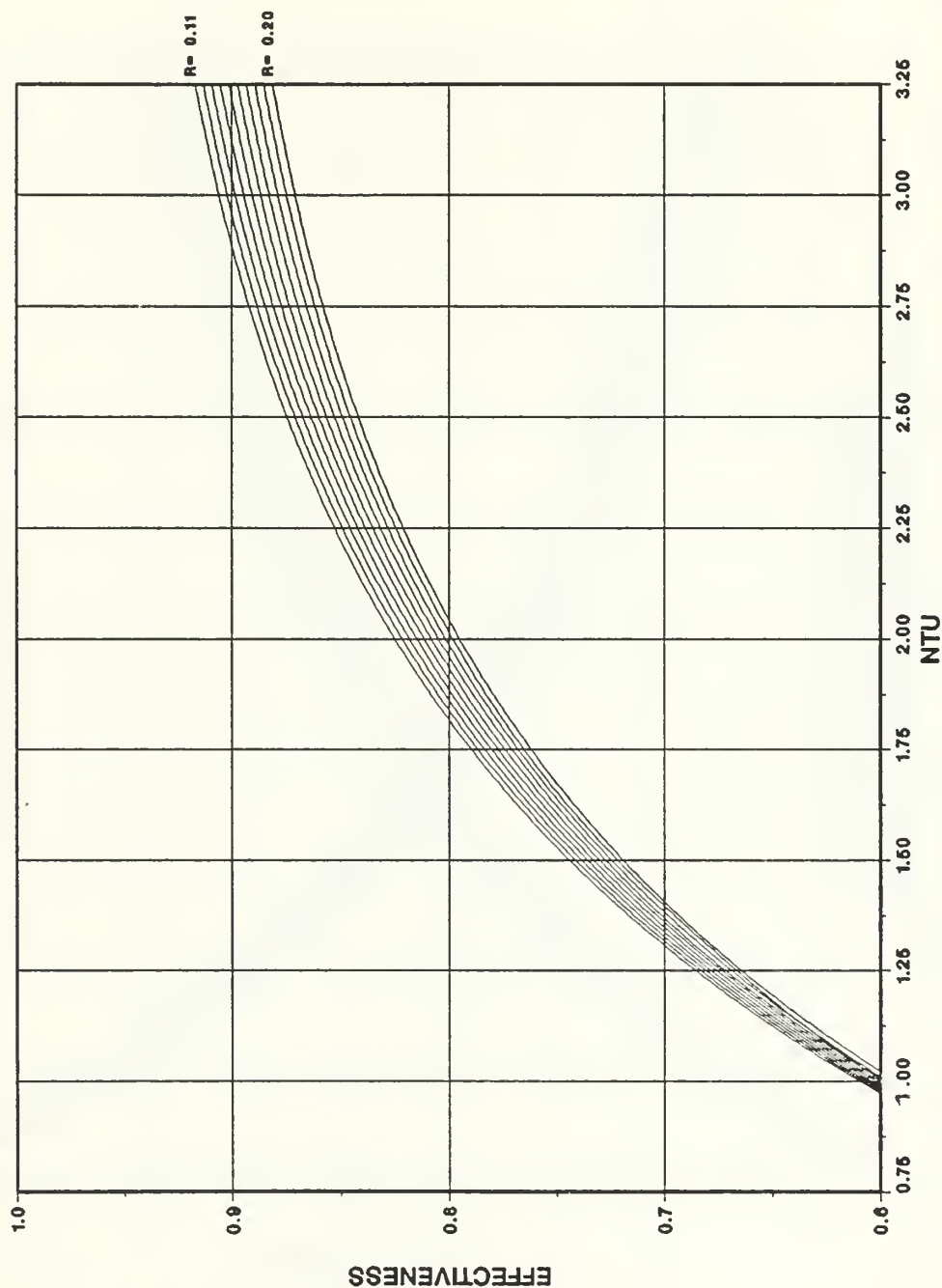


Figure M.3 1-3:2C Effectiveness vs. N_{tu} over Range of R from 0.11 to 0.2

EFFECTIVENESS VS. NTU

2 OUT OF 3 PASSES IN COUNTER FLOW
FOR R VARYING BY .01 FROM .21 TO 0.3

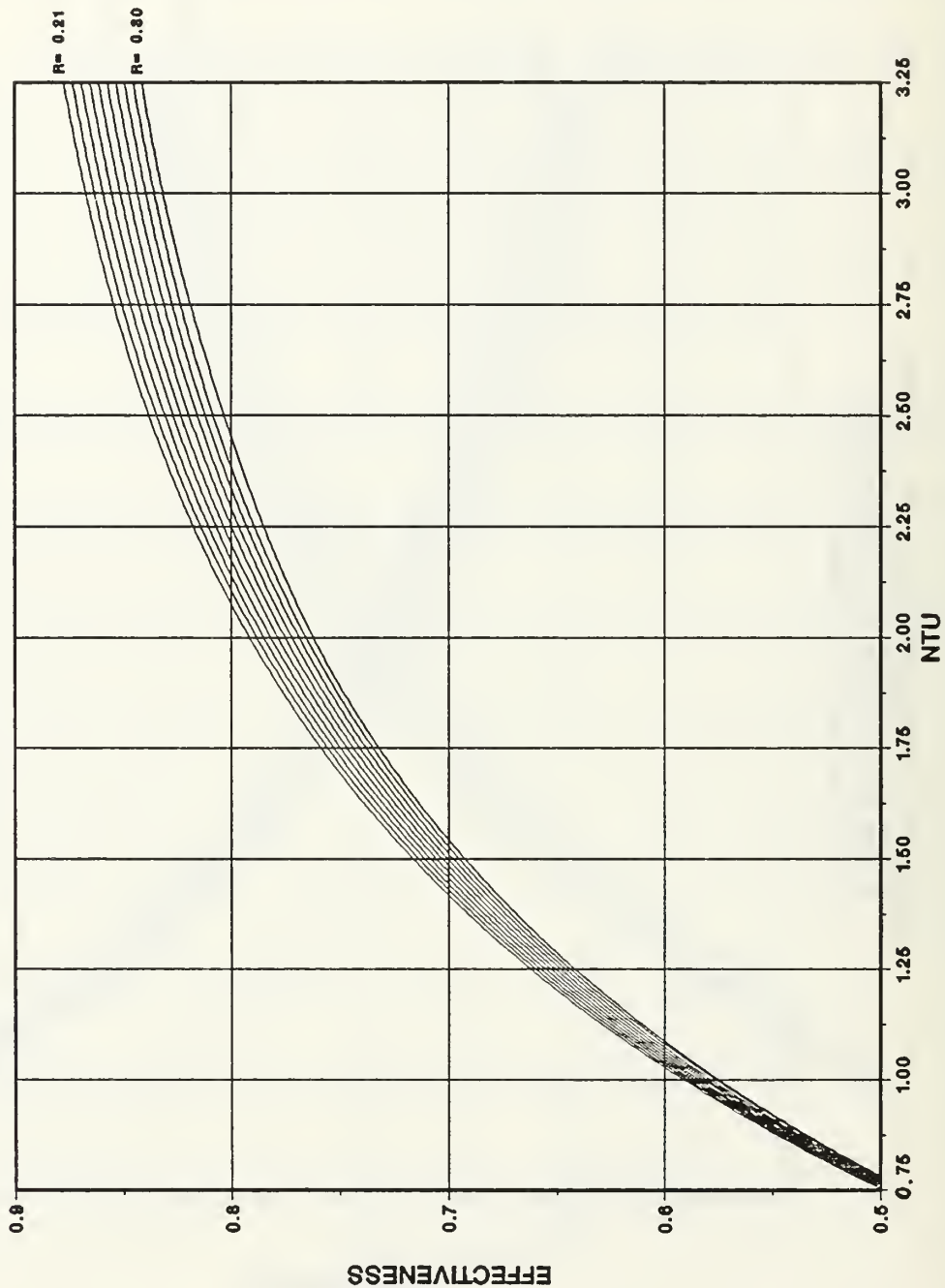


Figure M.4 1-3:2C Effectiveness vs. N_{tu} over Range of R from 0.21 to 0.3

EFFECTIVENESS VS. NTU 2 OUT OF 3 PASSES IN COUNTER FLOW FOR R VARING BY .01 FROM .31 TO 0.4

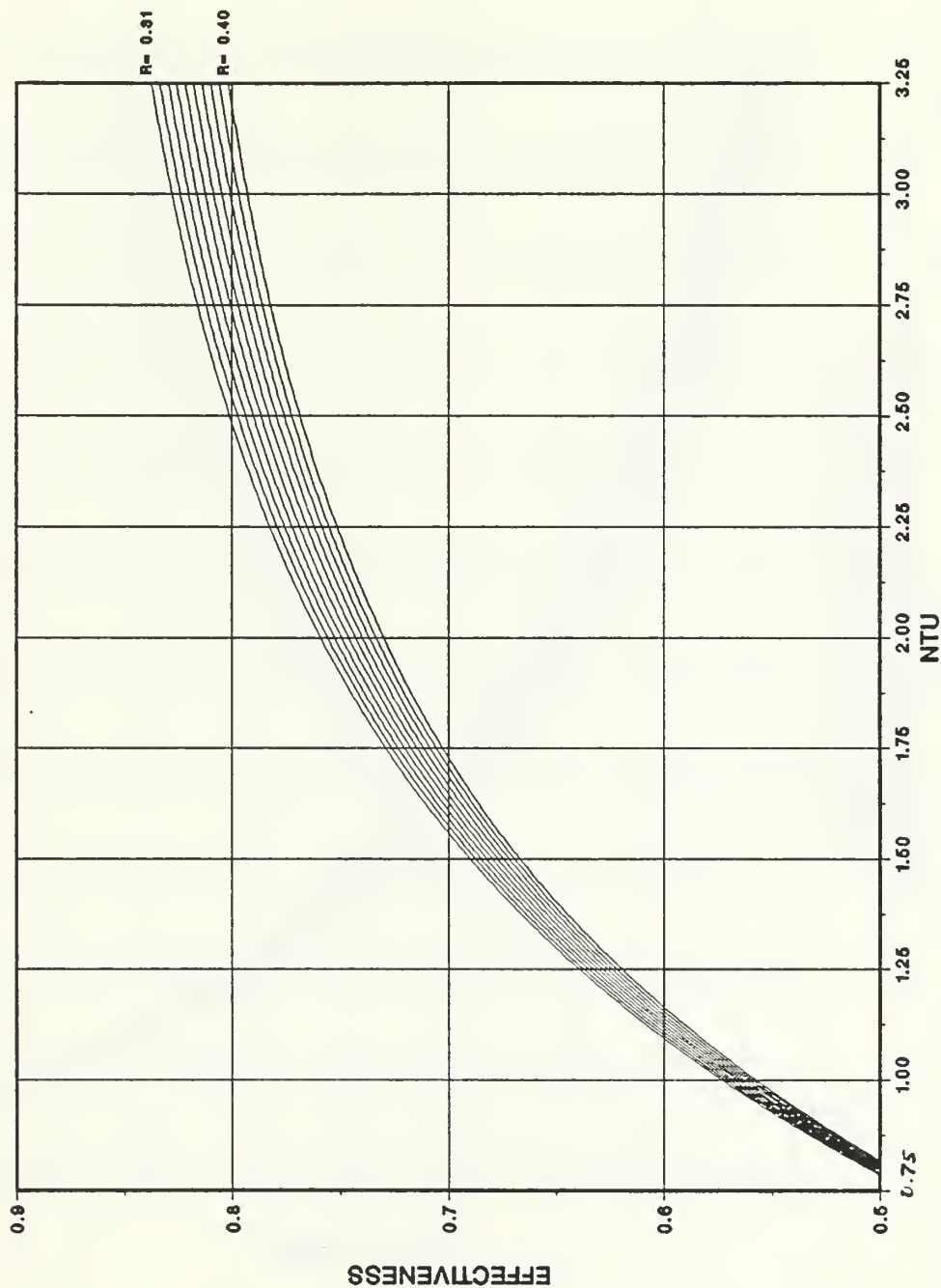


Figure M.5 1-3:2C Effectiveness vs. N_{tu} over Range of R from 0.31 to 0.4

EFFECTIVENESS VS. NTU **2 OUT OF 3 PASSES IN COUNTER FLOW** **FOR R VARING BY .01 FROM .41 TO 0.5**

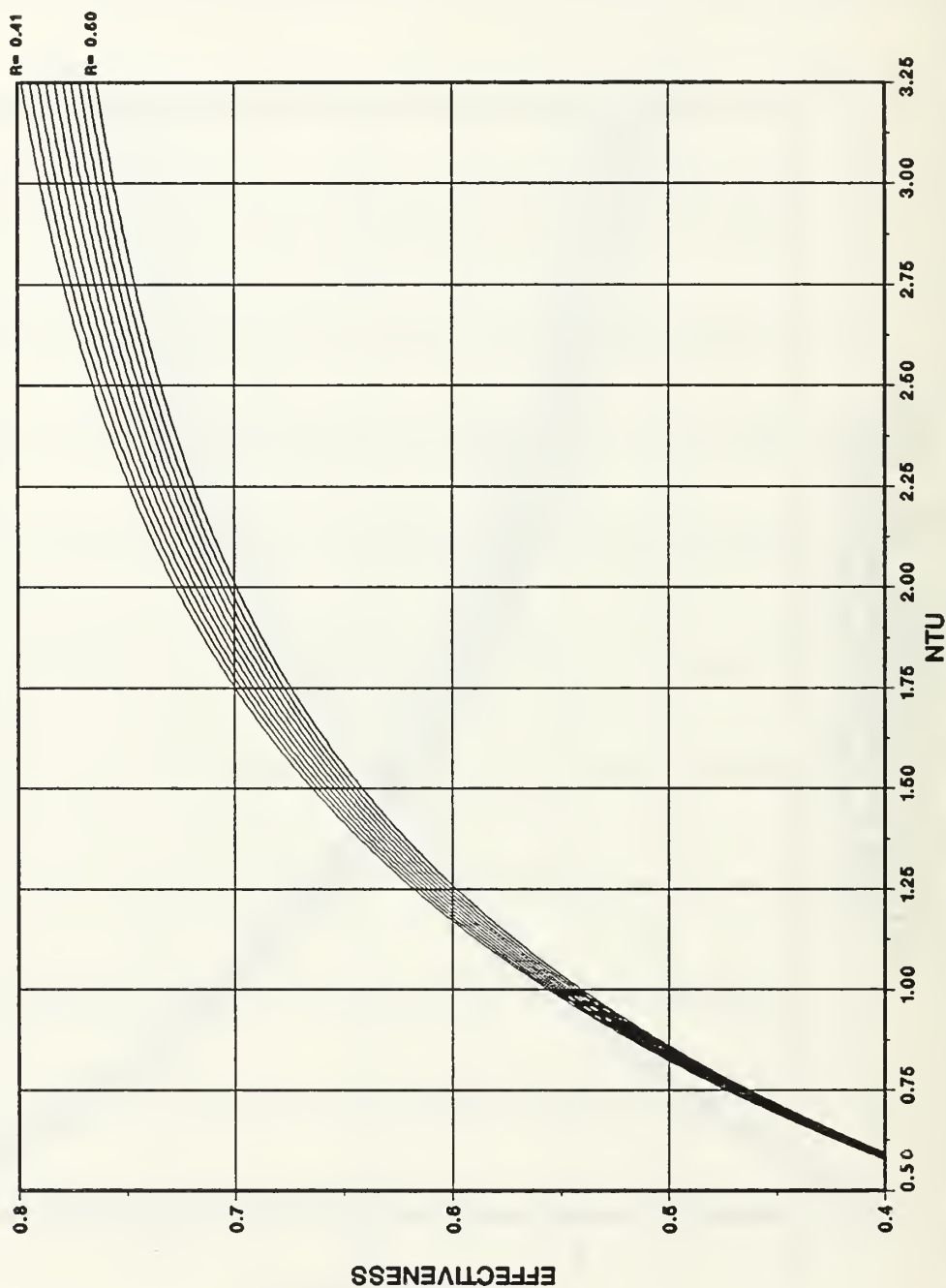


Figure M.6 1-3:2C Effectiveness vs. N_{tu} over Range of R from 0.41 to 0.5

EFFECTIVENESS VS. NTU

2 OUT OF 3 PASSES IN COUNTER FLOW
FOR R VARYING BY .01 FROM .51 TO 0.6

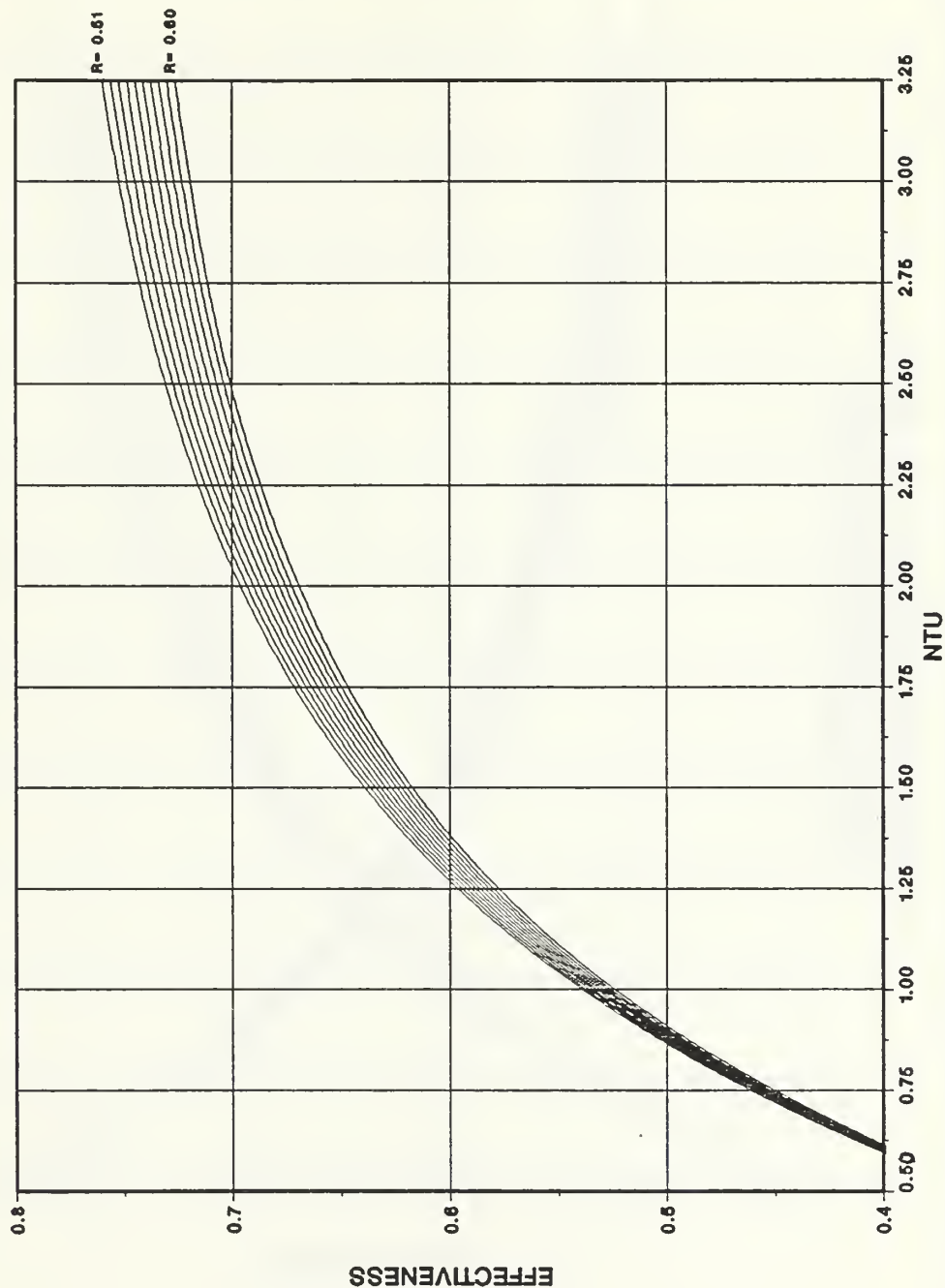


Figure M.7 1-3:2C Effectiveness vs. N_{tu} over Range of R from 0.51 to 0.6

EFFECTIVENESS VS. NTU

2 OUT OF 3 PASSES IN COUNTER FLOW
FOR R VARING BY .01 FROM .61 TO 0.7

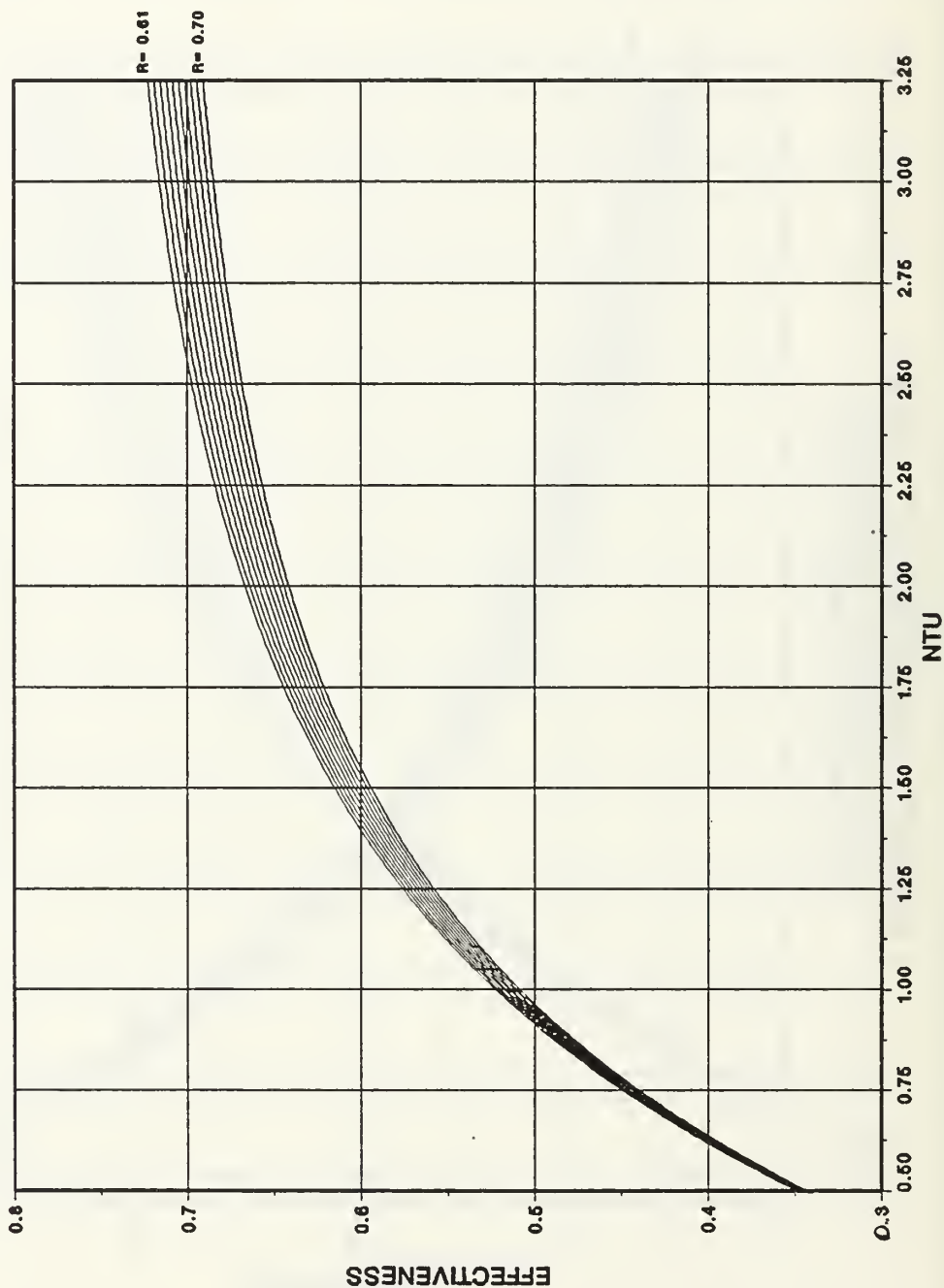


Figure M.8 1-3:2C Effectiveness vs. N_{tu} over Range of R from 0.61 to 0.7

EFFECTIVENESS VS. NTU

2 OUT OF 3 PASSES IN COUNTER FLOW
FOR R VARYING BY .01 FROM .71 TO 0.8

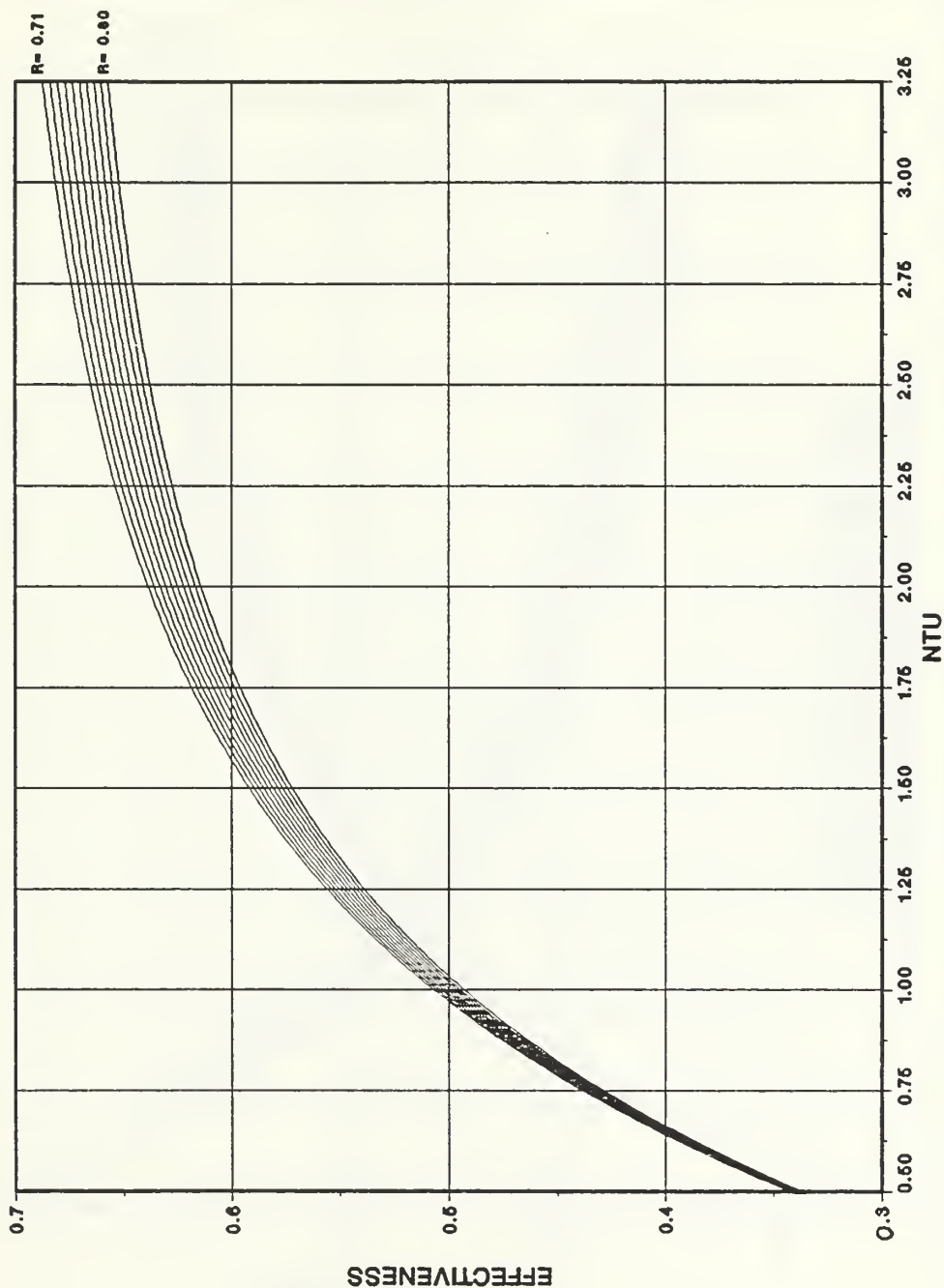


Figure M.9 1-3:2C Effectiveness vs. N_{tu} over Range of R from 0.71 to 0.8

EFFECTIVENESS VS. NTU **2 OUT OF 3 PASSES IN COUNTER FLOW** **FOR R VARING BY .01 FROM .81 TO 0.9**

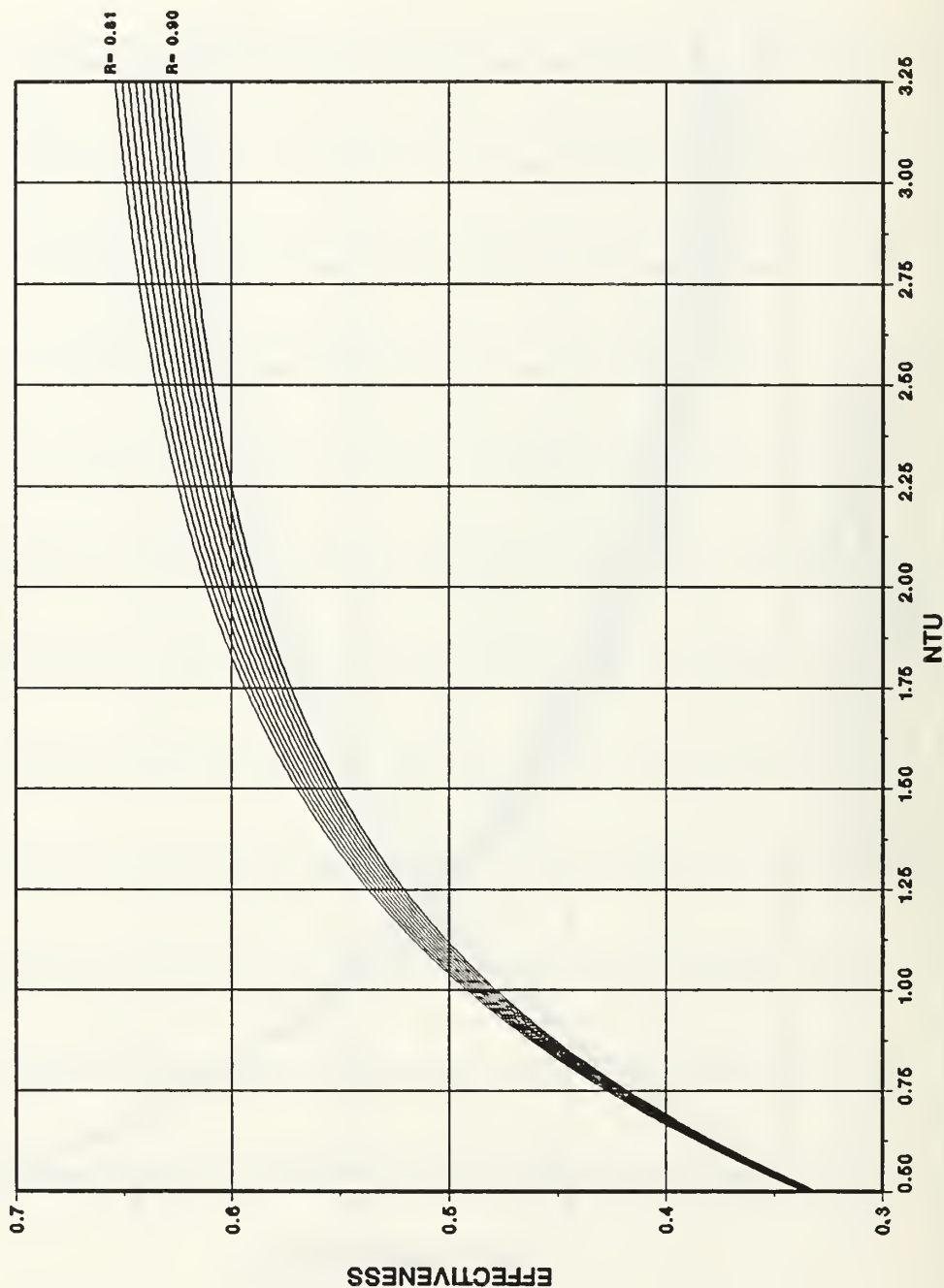


Figure M.10 1-3:2C Effectiveness vs. Ntu over Range of R from 0.81 to 0.9

EFFECTIVENESS VS. NTU

2 OUT OF 3 PASSES IN COUNTER FLOW
FOR R VARYING BY .01 FROM 0.9 TO 1.0

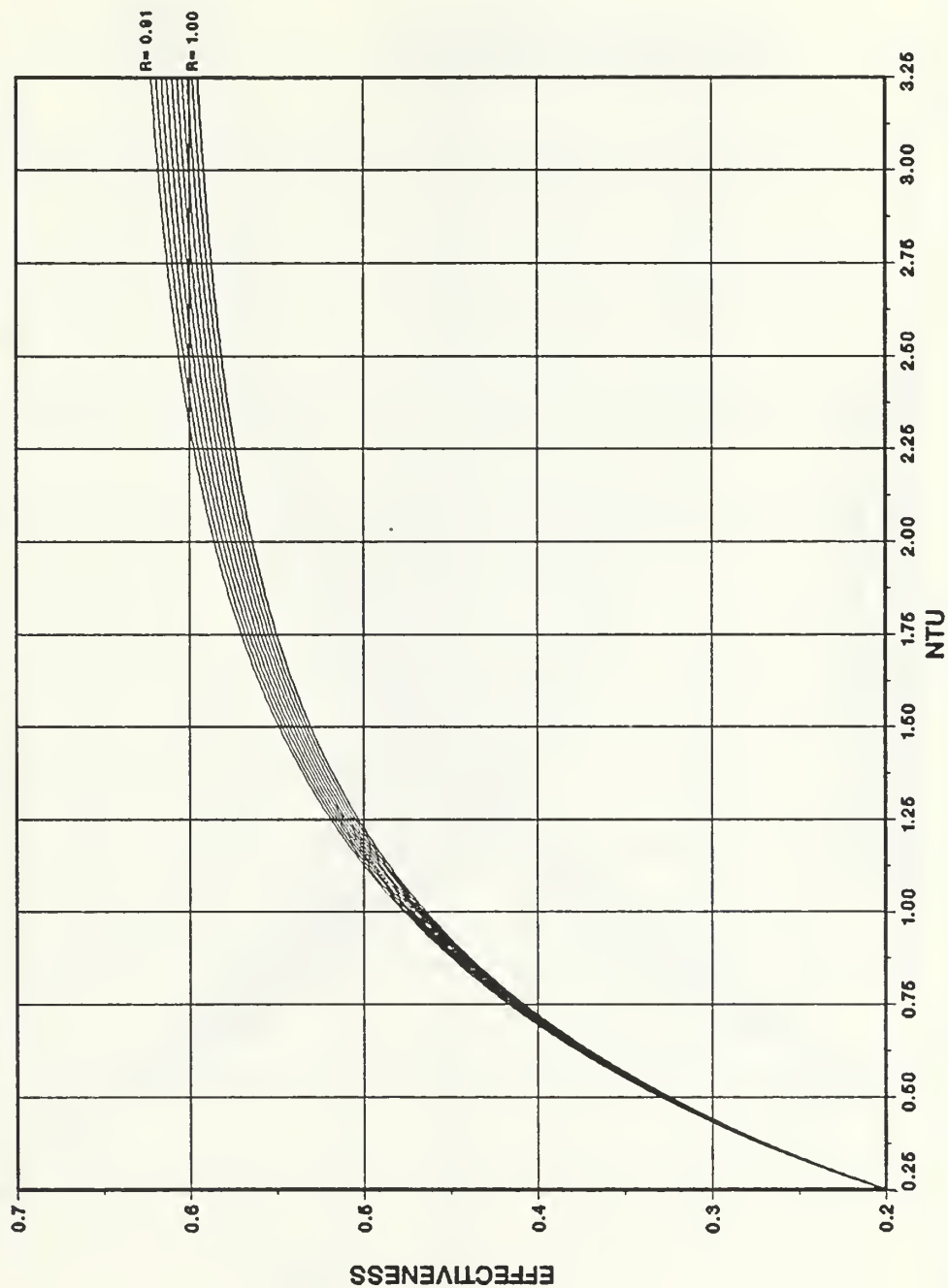


Figure M.11 1-3:2C Effectiveness vs. N_{tu} over Range of R from 0.9 to 1.0

APPENDIX N

1-3:2P EFFECTIVENESS VS. N_{tu} GRAPHS AT VARIOUS R VALUES

EFFECTIVENESS VS. NTU 2 OUT OF 3 PASSES IN PARALLEL FLOW

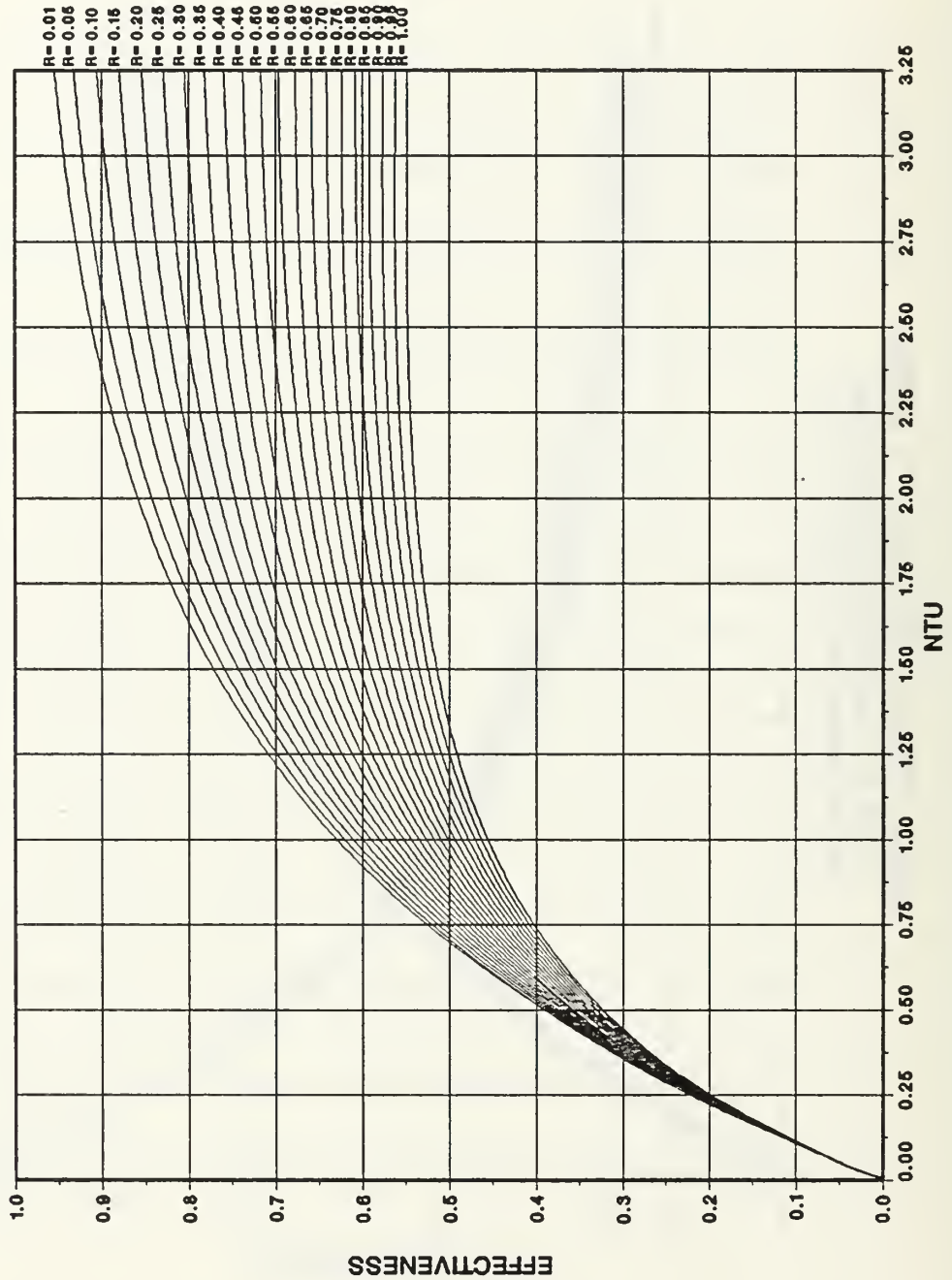


Figure N.1 1-3:2P Effectiveness vs. N_{tu} over Range of R from 0.01 to 1.0

EFFECTIVENESS VS. NTU **2 OUT OF 3 PASSES IN PARALLEL FLOW** **FOR R VARYING FROM .01 to 0.1**

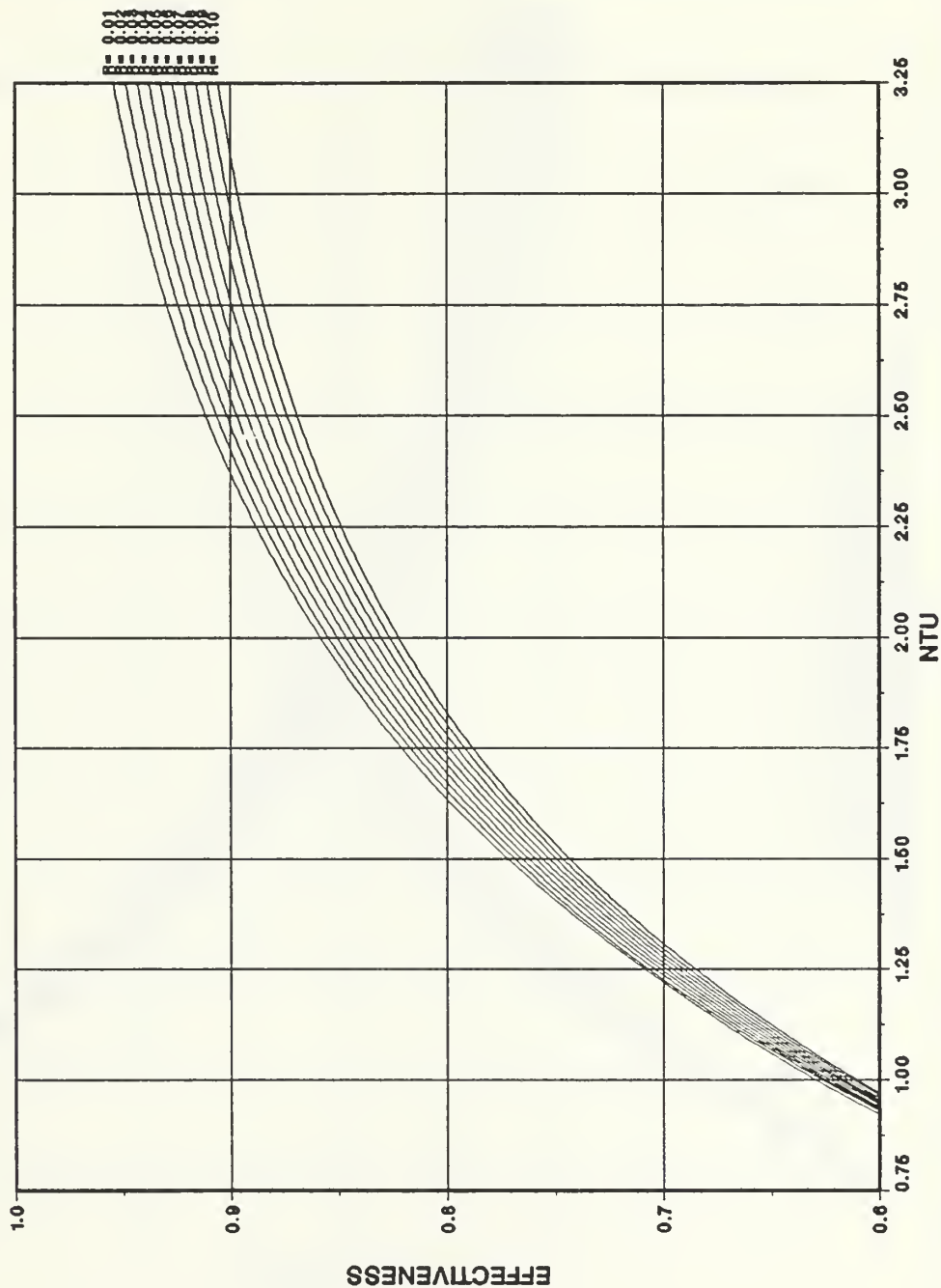


Figure N.2 1-3:2P Effectiveness vs. N_{tu} over Range of R from 0.01 to 0.1

EFFECTIVENESS VS. NTU **2 OUT OF 3 PASSES IN PARALLEL FLOW** **FOR R VARING FROM .11 TO 0.2**

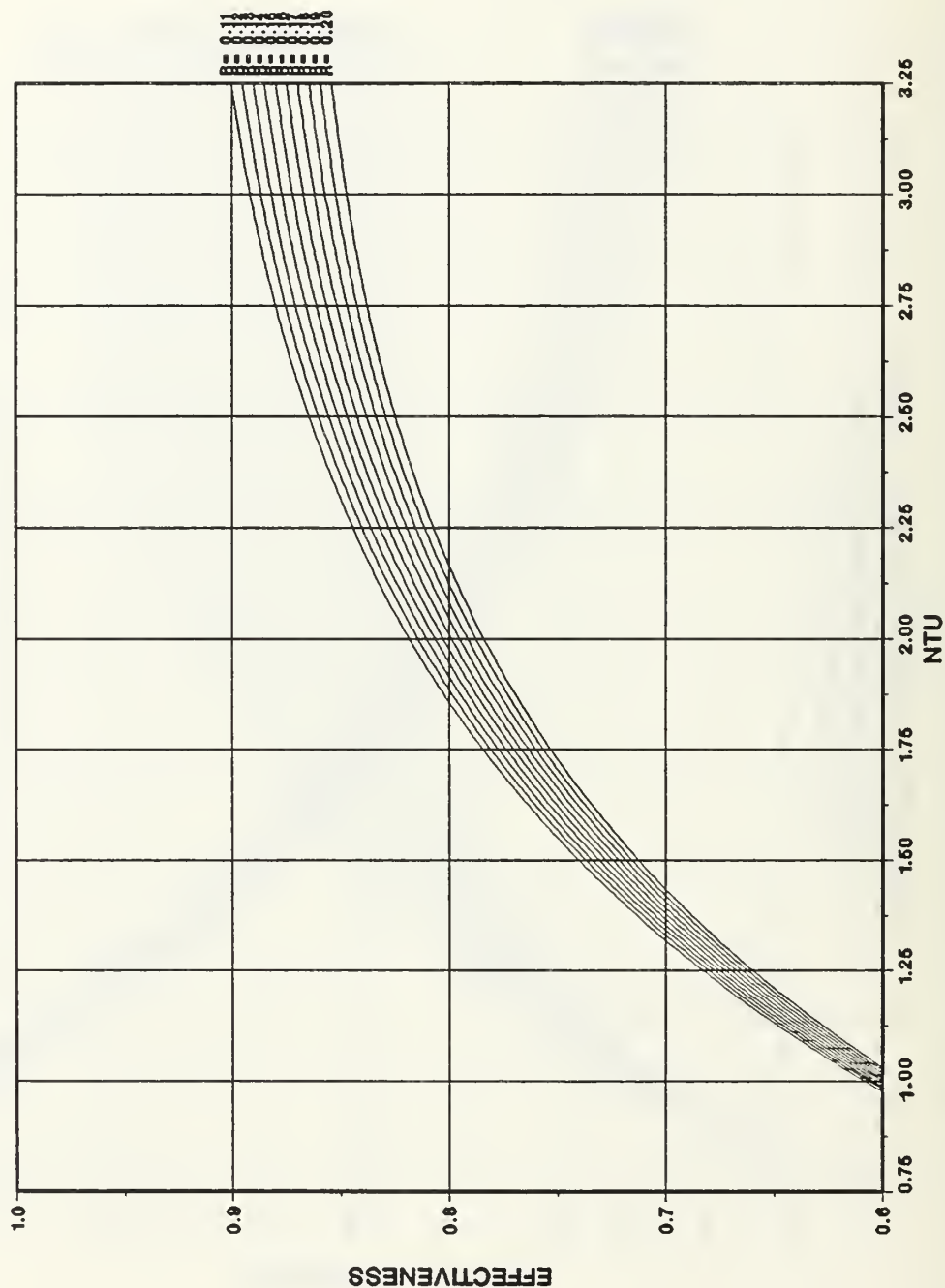


Figure N.3 1-3:2P Effectiveness vs. N_{tu} over Range of R from 0.11 to 0.2

EFFECTIVENESS VS. NTU **2 OUT OF 3 PASSES IN PARALLEL FLOW** **FOR R VARING FROM .21 to 0.3**

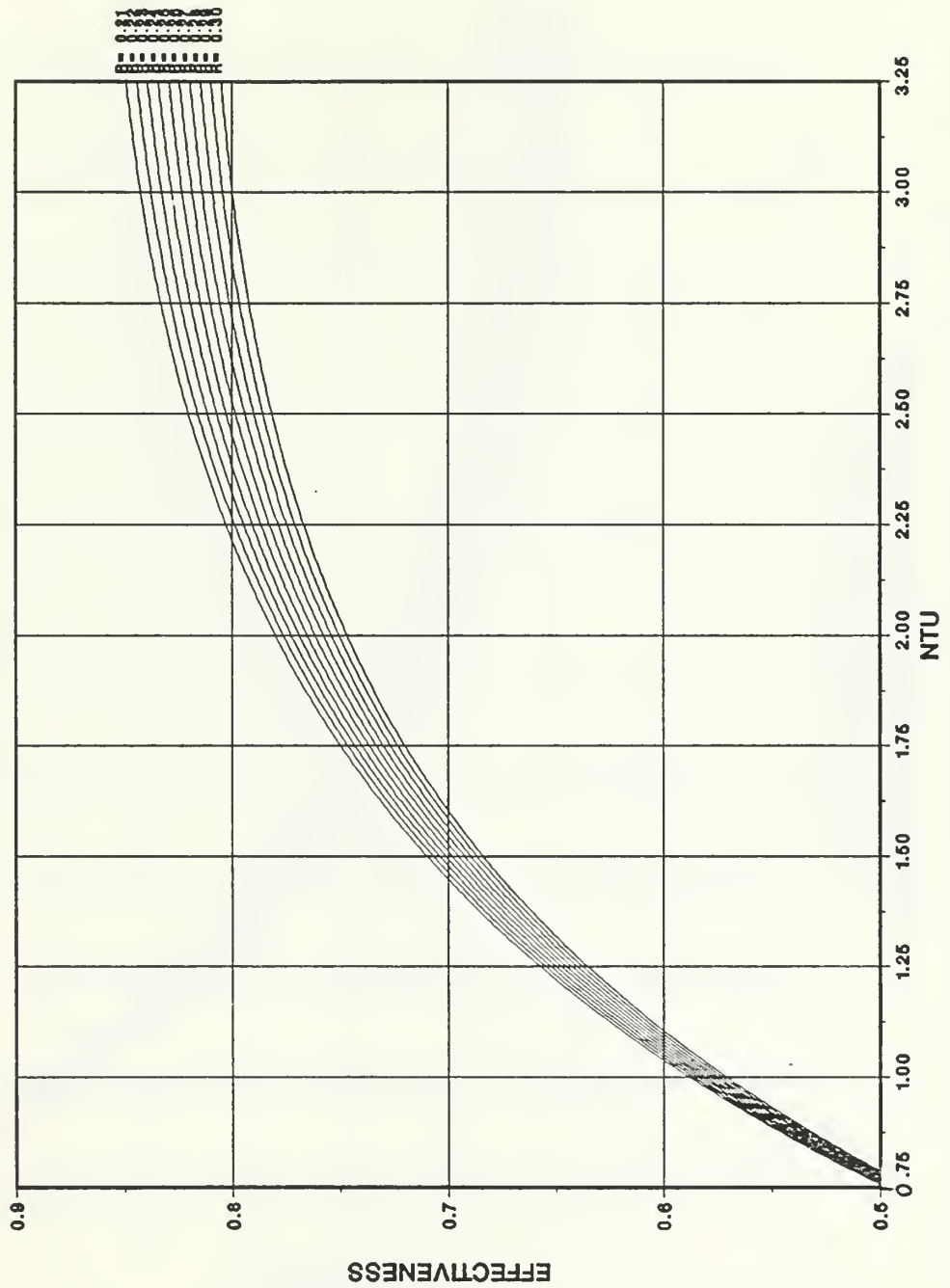


Figure N.4 1-3:2P Effectiveness vs. N_{tu} over Range of R from 0.21 to 0.3

EFFECTIVENESS VS. NTU
2 OUT OF 3 PASSES IN PARALLEL FLOW
FOR R VARYING FROM .31 TO 0.4

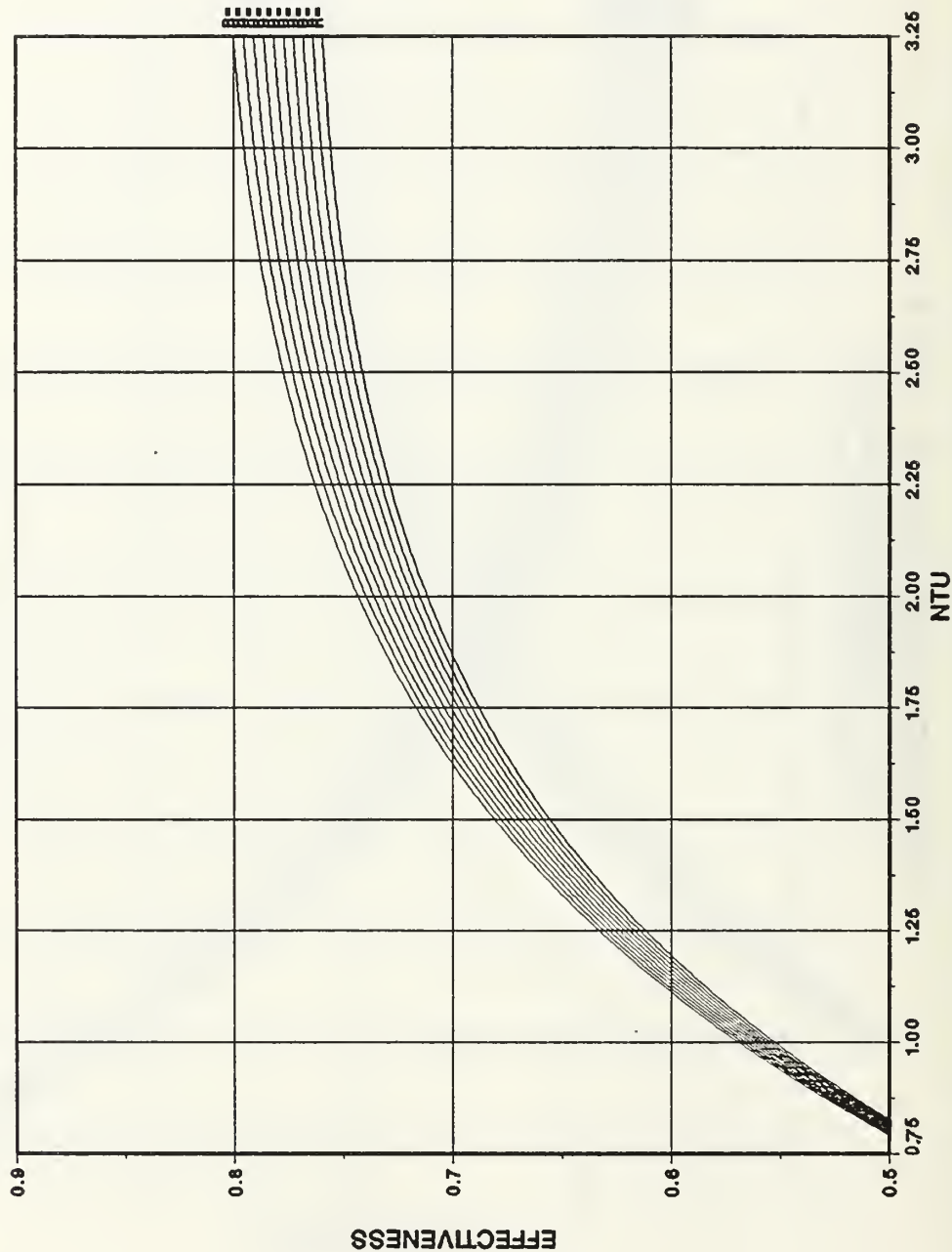


Figure N.5 1-3:2P Effectiveness vs. N_{tu} over Range of R from 0.31 to 0.4

EFFECTIVENESS VS. NTU **2 OUT OF 3 PASSES IN PARALLEL FLOW** **FOR R VARYING FROM .41 TO 0.5**

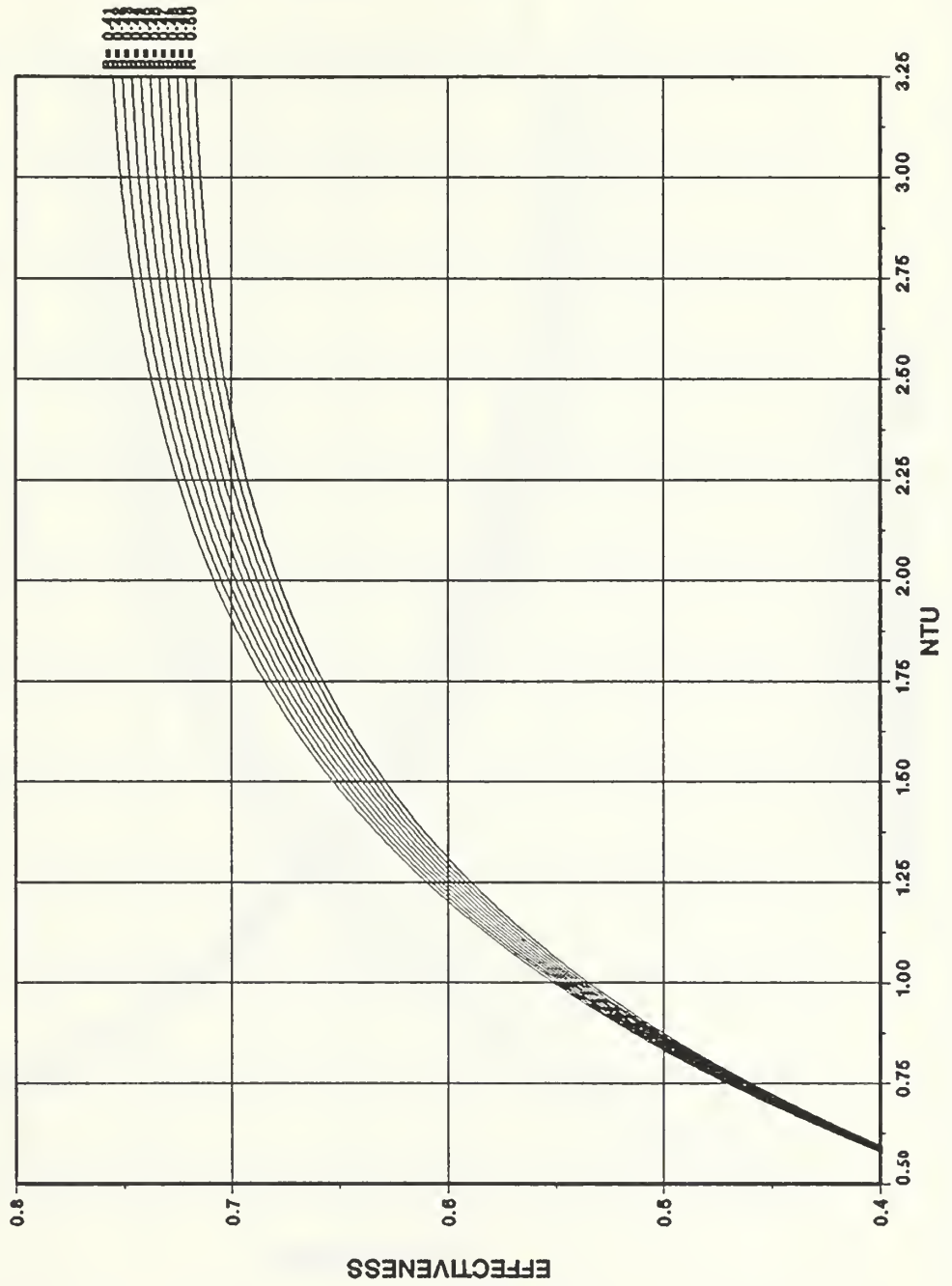


Figure N.6 1-3:2P Effectiveness vs. N_{tu} over Range of R from 0.41 to 0.5

EFFECTIVENESS VS. NTU **2 OUT OF 3 PASSES IN PARALLEL FLOW** **FOR R VARYING FROM .51 TO 0.6**

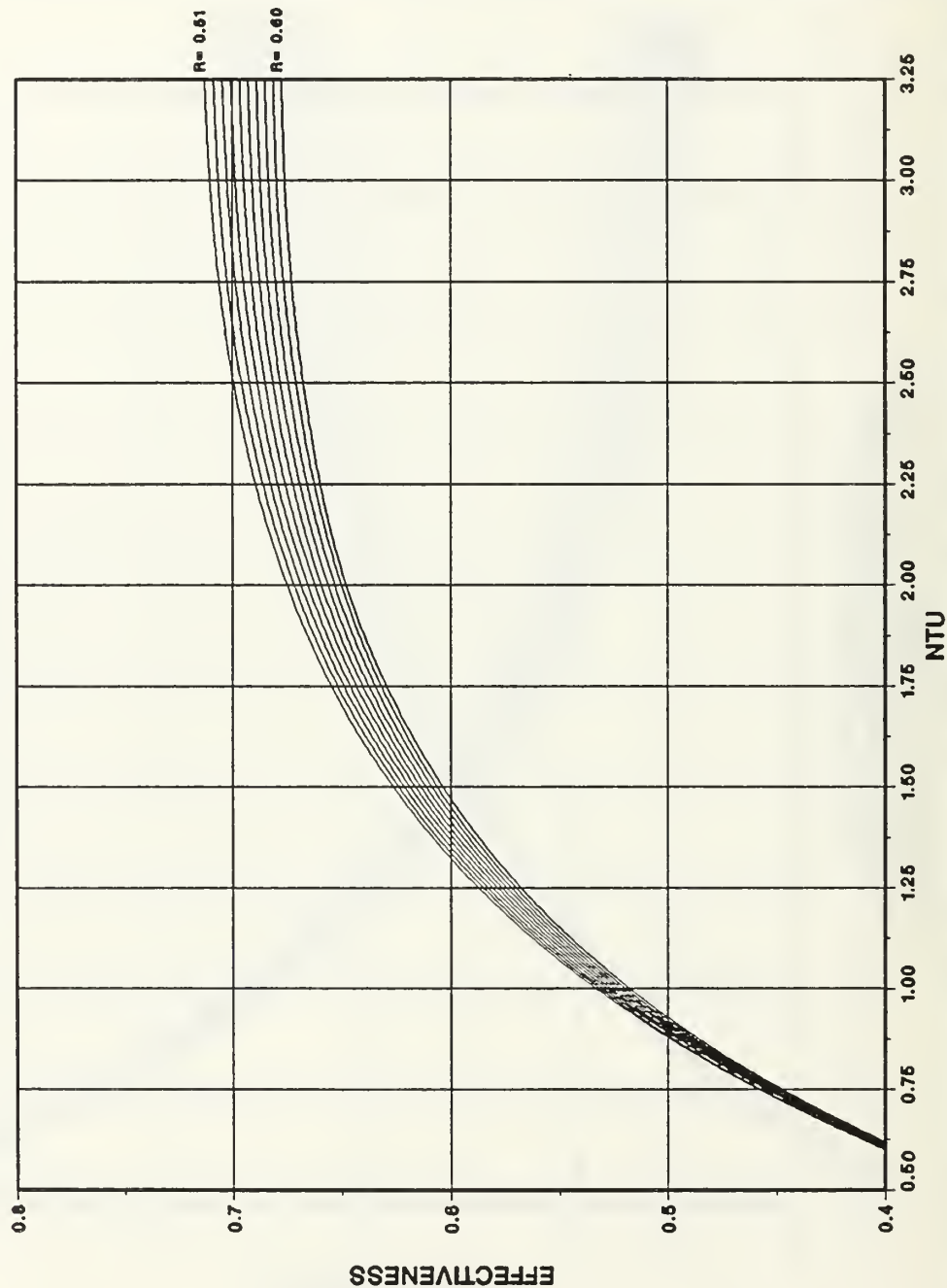


Figure N.7 1-3:2P Effectiveness vs. N_{tu} over Range of R from 0.51 to 0.6

EFFECTIVENESS VS. NTU **2 OUT OF 3 PASSES IN PARALLEL FLOW** **FOR R VARYING BY .01 FROM .61 TO 0.7**

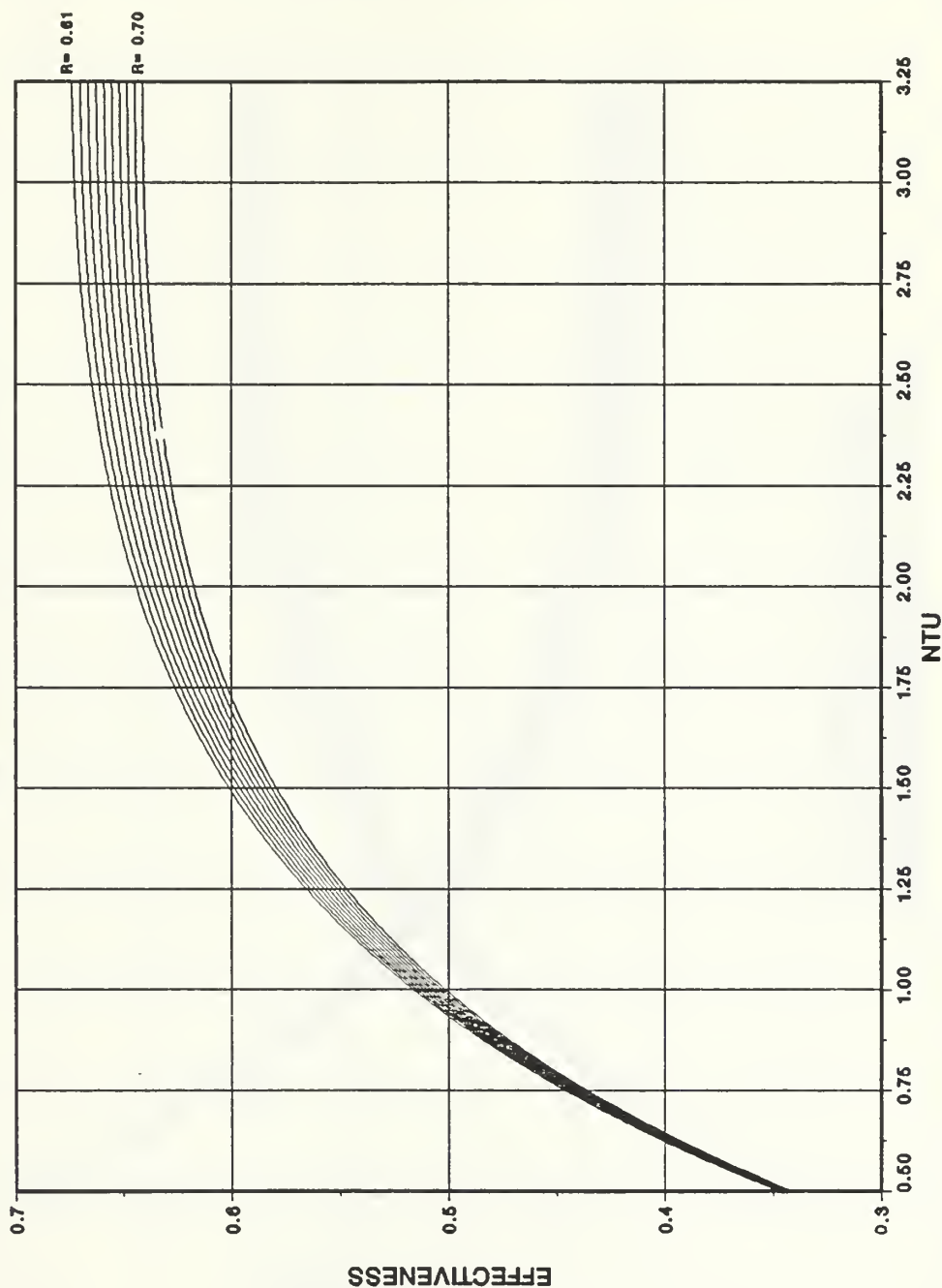


Figure N.8 1-3:2P Effectiveness vs. N_{tu} over Range of R from 0.61 to 0.7

EFFECTIVENESS VS. NTU **2 OUT OF 3 PASSES IN PARALLEL FLOW** **FOR R VARYING BY .01 FROM .71 TO 0.8**

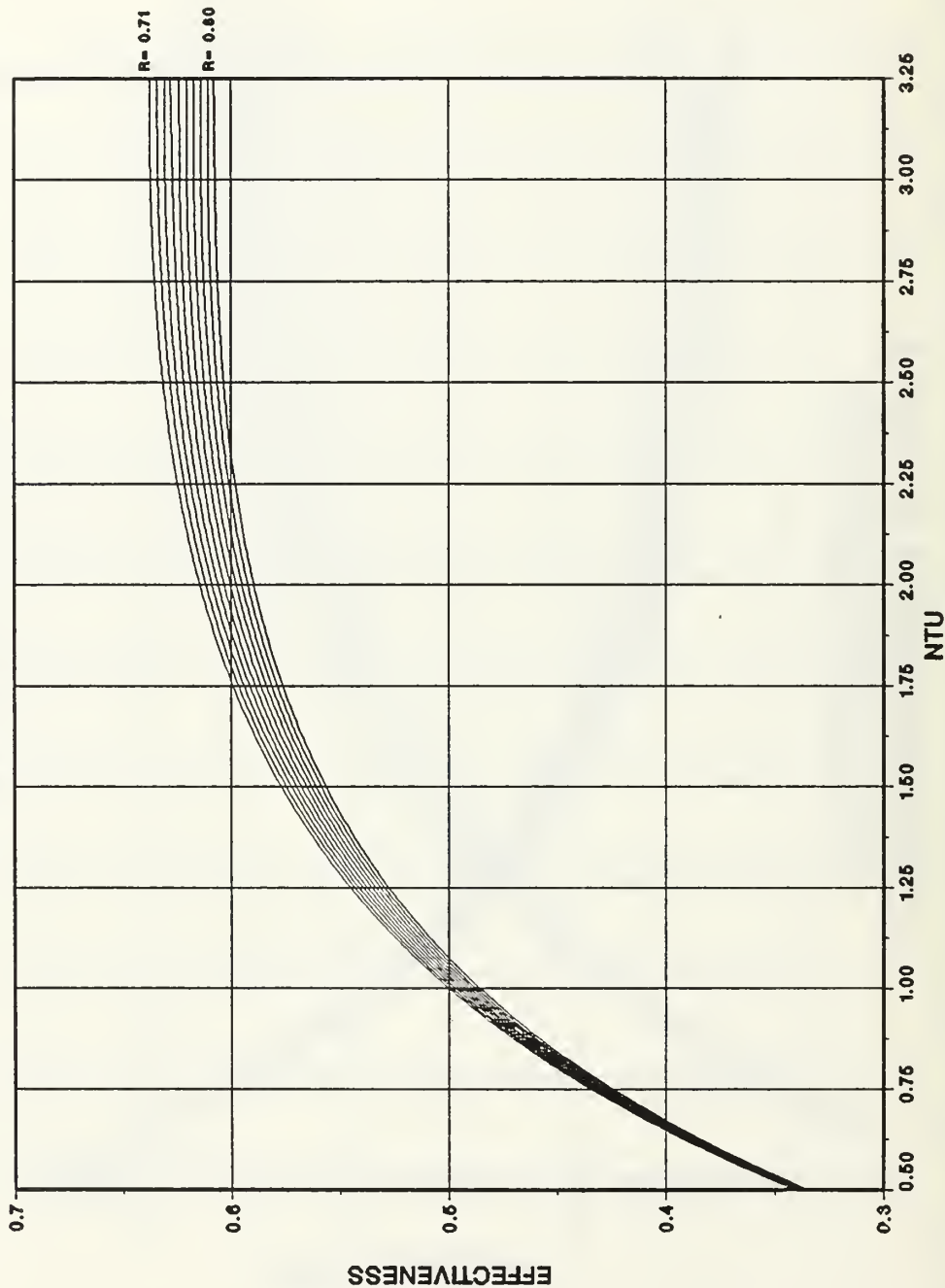


Figure N.9 1-3:2P Effectiveness vs. N_{tu} over Range of R from 0.71 to 0.8

EFFECTIVENESS VS. NTU **2 OUT OF 3 PASSES IN PARALLEL FLOW** **FOR R VARING BY .01 FROM .81 TO 0.9**

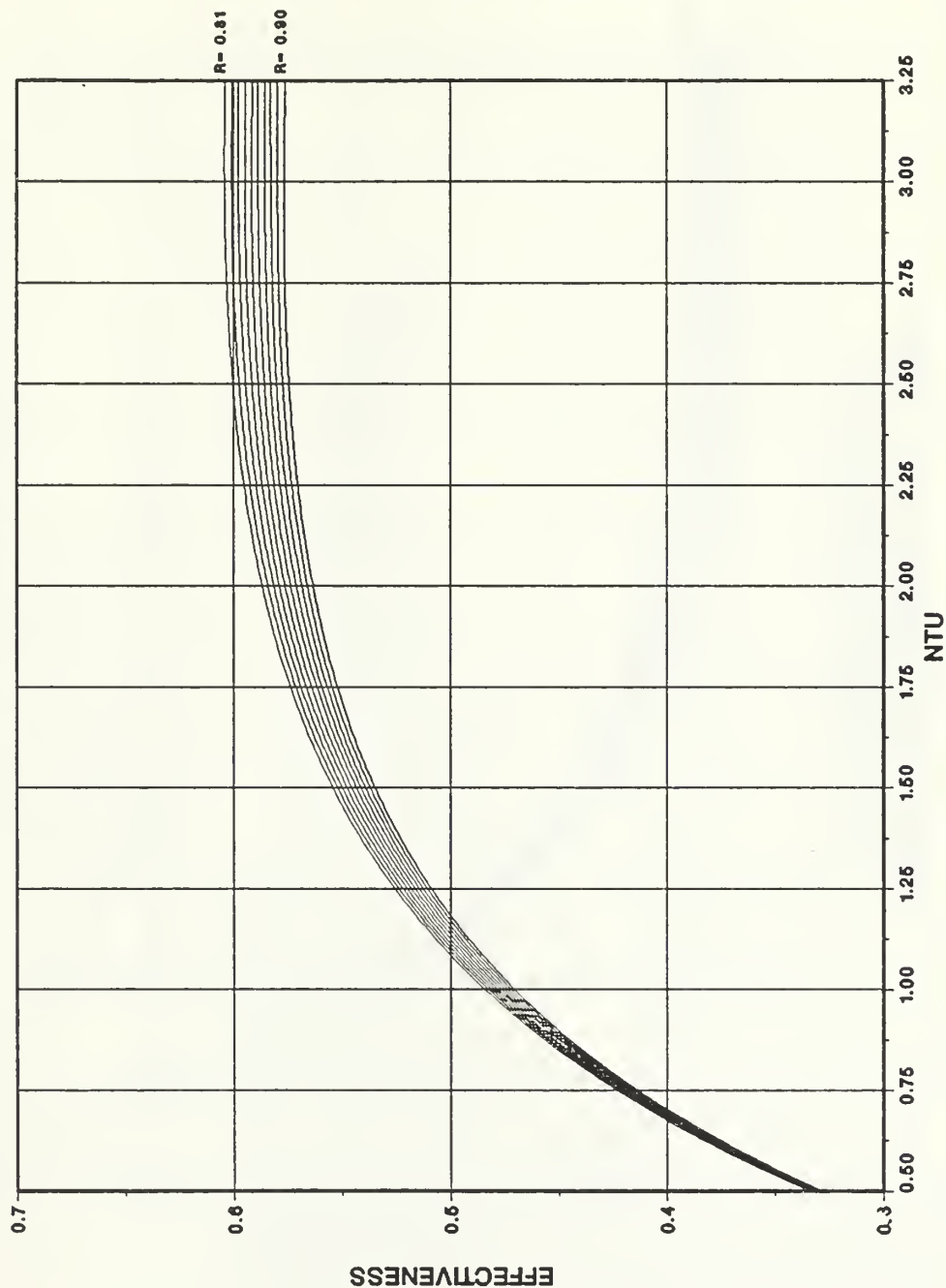


Figure N.10 1-3:2P Effectiveness vs. N_{tu} over Range of R from 0.81 to 0.9

EFFECTIVENESS VS. NTU 2 OUT OF 3 PASSES IN PARALLEL FLOW FOR R VARYING BY .01 FROM 0.9 TO 1.0

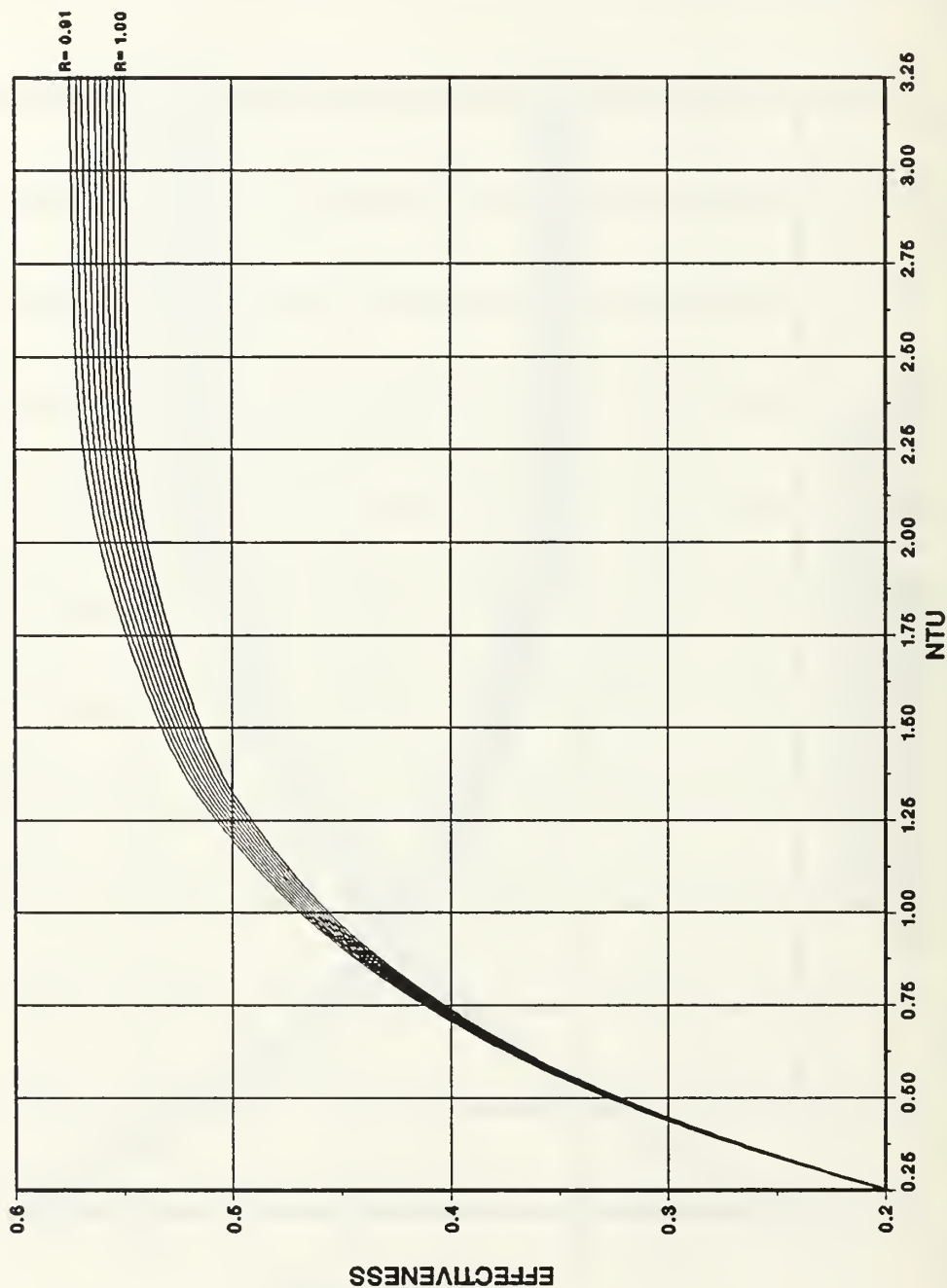


Figure N.11 1-3:2P Effectiveness vs. N_{tu} over Range of R from 0.91 to 1.0

APPENDIX O
SAMPLE DISSPLAY PROGRAM USED FOR GRAPHING DATA

```

C *****
C *
C *
C *
C *
C *
C *
C *
C *
C *****
C
C      DISPLAY GRAPHING ROUTINE
C      by
C      LCDR MARK S O'HARE U.S.N
C      8 MAY 1985
C      NAVAL POSTGRADUATE SCHOOL, MONTEREY, CA
C *****
C
C      CALL DISPLA GRAPHICS PACKAGE
C      DIMENSION X1(12),Y1(12),X3(12),Y3(12),X4(12),Y4(12)
C      DIMENSION X2(12),Y2(12),X6(12),Y6(12),X10(12),Y10(12),X11(12),Y11(12),X12(12),Y12(12)
C      DIMENSION X5(12),Y5(12),X8(12),Y8(12),X9(12),Y9(12),X10(12),Y10(12),X11(12),Y11(12),X12(12),Y12(12)
C      DIMENSION X7(12),Y7(12),X14(12),Y14(12),X15(12),Y15(12),X16(12),Y16(12),X17(12),Y17(12),X18(12),Y18(12)
C      DIMENSION X13(12),Y13(12),X14(12),Y14(12),X15(12),Y15(12),X16(12),Y16(12),X17(12),Y17(12),X18(12),Y18(12)
C      DIMENSION X19(12),Y19(12),X20(12),Y20(12),X21(12),Y21(12)
C      DIMENSION Y19(12),Y20(12),Y21(12)
C      DIMENSION WW(21)
C
C      THIS IS THE DISTANCE OF THE VALUE FOR R
C      TT=3.315
C      THIS IS THE DISTANCE OF 'R='
C      T=3.265
C
C      CALL TEK618
C      CALL COMPRS
C      ***** START LEVEL 1 WORK *****
C      CALL BCOMON(10*21+2)
C      DATA WW/0.01,0.05,0.10,0.15,0.20,0.25,0.30,0.35,0.4,0.45,0.5,
C      *0.55,0.6,0.65,0.7,0.75,0.8,0.85,0.9,0.95,1.0/
C      FORMAT (6X,F4.2,3X,F6.4)
C      DO 20 I=1,11
C      READ (21,1000) X1(I),Y1(I)
C      CONTINUE
C      DO 30 I=1,11
C      READ (22,1000) X2(I),Y2(I)
C      CONTINUE
C      DO 40 I=1,11
C      READ (23,1000) X3(I),Y3(I)
C      CONTINUE
C      DO 50 I=1,11

```

```

50      READ (24,1000) X4(I),Y4(I)
        CONTINUE
        DO 60 I=1,11
          READ (25,1000) X5(I),Y5(I)
          CONTINUE
60      DO 70 I=1,11
          READ (26,1000) X6(I),Y6(I)
          CONTINUE
70      DO 80 I=1,11
          READ (27,1000) X7(I),Y7(I)
          CONTINUE
80      DO 90 I=1,11
          READ (28,1000) X8(I),Y8(I)
          CONTINUE
90      DO 100 I=1,11
          READ (29,1000) X9(I),Y9(I)
          CONTINUE
100     DO 110 I=1,11
          READ (30,1000) X10(I),Y10(I)
          CONTINUE
110     DO 120 I=1,11
          READ (31,1000) X11(I),Y11(I)
          CONTINUE
120     DO 130 I=1,11
          READ (32,1000) X12(I),Y12(I)
          CONTINUE
130     DO 140 I=1,11
          READ (33,1000) X13(I),Y13(I)
          CONTINUE
140     DO 150 I=1,11
          READ (34,1000) X14(I),Y14(I)
          CONTINUE
150     DO 160 I=1,11
          READ (35,1000) X15(I),Y15(I)
          CONTINUE
160     DO 170 I=1,11
          READ (36,1000) X16(I),Y16(I)
          CONTINUE
170     DO 180 I=1,11
          READ (37,1000) X17(I),Y17(I)
          CONTINUE
180     DO 190 I=1,11
          READ (38,1000) X18(I),Y18(I)
          CONTINUE
190     DO 200 I=1,11
          READ (39,1000) X19(I),Y19(I)
          CONTINUE
200     DO 210 I=1,11

```



```

210 READ (40,1000) X20(I),Y20(I)
CONTINUE
DO 220 I=1,11
READ (41,1000) X21(I),Y21(I)
CONTINUE
CALL NOBRDR
CALL SWISSM
CALL BASALF ('STANDARD')
CALL MIXALF ('L/CSTD')
CALL HWRROT (COMIC)
CALL SHDCHR (90,1,0.005,1)
CALL HEIGHT (1)
CALL HWSCAL ('SCREEN')
CALL PAGE (14,0,11,0)
CALL XNAME ('NTUS',100)
CALL YNAME ('EFFECTIVENESS',100)
CALL AREA2D (11,0,8.5)
CALL HEADIN ('EFFECTIVENESS VS. NTUS',100,2,0,2)
CALL HEADIN ('2 OUT OF 3 PASSES IN COUNTER FLOW',100,1,0,2)
CALL YTICKS (2)
CALL XTICKS (2)
CALL YAXANG (180)
CALL GRAF (0,0,0,25,3.25,0,0,0,10,1,0)
CALL HEIGHT (10)
CALL POLY5
CALL CURVE (X1,Y1,11,0)
W=WW (1)
Z=Y1 (1)
CALL RLREAL (W,2,TT,Z)
CALL RLMESS (R=,2,T,Z)
CALL CURVE (X2,Y2,11,0)
W=WW (2)
Z=Y2 (1)
CALL RLREAL (W,2,TT,Z)
CALL RLMESS (R=,2,T,Z)
CALL CURVE (X3,Y3,11,0)
W=WW (3)
Z=Y3 (1)
CALL RLREAL (W,2,TT,Z)
CALL RLMESS (R=,2,T,Z)
CALL CURVE (X4,Y4,11,0)
W=WW (4)
Z=Y4 (1)
CALL RLREAL (W,2,TT,Z)
CALL RLMESS (R=,2,T,Z)
CALL CURVE (X5,Y5,11,0)
W=WW (5)
Z=Y5 (1)

```

```

CALL RLREAL (W, 2, TT, Z)
CALL RLMESS (R= $ 2, T, Z)
CALL CURVE (X6, Y6, I1, 0)
W=WW(6)
Z=Y6(11)
CALL RLREAL (W, 2, TT, Z)
CALL RLMESS (R= $ 2, T, Z)
CALL CURVE (X7, Y7, I1, 0)
W=WW(7)
Z=Y7(11)
CALL RLREAL (W, 2, TT, Z)
CALL RLMESS (R= $ 2, T, Z)
CALL CURVE (X8, Y8, I1, 0)
W=WW(8)
Z=Y8(11)
CALL RLREAL (W, 2, TT, Z)
CALL RLMESS (R= $ 2, T, Z)
CALL CURVE (X9, Y9, I1, 0)
W=WW(9)
Z=Y9(11)
CALL RLREAL (W, 2, TT, Z)
CALL RLMESS (R= $ 2, T, Z)
CALL CURVE (X10, Y10, I1, 0)
W=WW(10)
Z=Y10(11)
CALL RLREAL (W, 2, TT, Z)
CALL RLMESS (R= $ 2, T, Z)
CALL CURVE (X11, Y11, I1, 0)
W=WW(11)
Z=Y11(11)
CALL RLREAL (W, 2, TT, Z)
CALL RLMESS (R= $ 2, T, Z)
CALL CURVE (X12, Y12, I1, 0)
W=WW(12)
Z=Y12(11)
CALL RLREAL (W, 2, TT, Z)
CALL RLMESS (R= $ 2, T, Z)
CALL CURVE (X13, Y13, I1, 0)
W=WW(13)
Z=Y13(11)
CALL RLREAL (W, 2, TT, Z)
CALL RLMESS (R= $ 2, T, Z)
CALL CURVE (X14, Y14, I1, 0)
W=WW(14)
Z=Y14(11)
CALL RLREAL (W, 2, TT, Z)
CALL RLMESS (R= $ 2, T, Z)
CALL CURVE (X15, Y15, I1, 0)

```

```

W=WW(15)
Z=Y15(11)
CALL RLREAL (W,2,TT,Z)
CALL RLMESS (R=$,2,T,Z)
CALL CURVE (X16,Y16,11,0)
W=WW(16)
Z=Y16(11)
CALL RLREAL (W,2,TT,Z)
CALL RLMESS (R=$,2,T,Z)
CALL CURVE (X17,Y17,11,0)
W=WW(17)
Z=Y17(11)
CALL RLREAL (W,2,TT,Z)
CALL RLMESS (R=$,2,T,Z)
CALL CURVE (X18,Y18,11,0)
W=WW(18)
Z=Y18(11)
CALL RLREAL (W,2,TT,Z)
CALL RLMESS (R=$,2,T,Z)
CALL CURVE (X19,Y19,11,0)
W=WW(19)
Z=Y19(11)
CALL RLREAL (W,2,TT,Z)
CALL RLMESS (R=$,2,T,Z)
CALL CURVE (X20,Y20,11,0)
W=WW(20)
Z=Y20(11)
CALL RLREAL (W,2,TT,Z)
CALL RLMESS (R=$,2,T,Z)
CALL CURVE (X21,Y21,11,0)
W=WW(21)
Z=Y21(11)
CALL RLREAL (W,2,TT,Z)
CALL RLMESS (R=$,2,T,Z)
***** START LEVEL 2 WORK *****
CALL FRAME
***** START LEVEL 3 WORK *****
CALL GRID(1,1)
CALL ENDPL(0)
CALL DONEPL
STOP
END

```

C

C

APPENDIX P

POLYNOMIAL REGRESSION CURVEFIT PROGRAM

PROGRAM POLYFIT

PURPOSE: DO AN NTH ORDER LEAST-SQUARES FIT OF THE INPUT VALUES
"X" AND "Y".

INPUT: I) X.
II) Y.

OUTPUT: I) MEAN OF X.
II) RANGE OF X.
III) ORDER OF THE FIT.
IV) COEFFICIENTS IN DOUBLE PRECISION.
V) R.M.S. ERROR OF THE RESIDUALS.

CALL: I) CURFIT(IORDER,NITEMS,X,Y,AA)
II) SOLVE(NR,C)
III) FUNCTION AMAX(X,NITEMS)
IV) FUNCTION AMIN(X,NITEMS)

INTEGER I,NITEMS,MAXORD,J,K,L,M,N
DOUBLE PRECISION AA(40)
DIMENSION X(11),Y(11),YCOMP(11),ONE(11,2),TWO(11,2)
COMMON IDIAGN

1. ZERO ALL VALUES THAT WILL BE USED TO COMPUTE SUMS.

RMSSUM = 0.0

2. INPUT THE DATA.

IDIAGN=0
WRITE(6,100)
FORMAT(2X,MAXIMUM ORDER OF THE FIT?)

C100

```

120      FORMAT(2X,' ',')
C      READ(5,*) MAXORD
C      MAXORD=5

10      DO 10 I=1,11
C          READ(1,*) ONE(I,1), TWO(I,2)
C          X(I) = ONE(I,1)
C          Y(I) = TWO(I,2)
C      CONTINUE

NITEMS = I - 2

3.      COMPUTE THE LEAST-SQUARES COEFFICIENTS BY CALLING "CURFIT()".
        THE COEFFICIENTS ARE RETURNED IN "AA()" SUCH THAT:

            Y=AA(1)+AA(2)*X+...+AA(N)*(X**N)

CALL CURFIT(MAXORD,NITEMS,X,Y,AA)

4.      COMPUTE THE RESIDUALS AND THE R.M.S. ERROR OF THE RESIDUALS.

DO 90 I = 1,NITEMS
    YCOMP(I) = 0.0
    IJUNK = MAXORD + 1
    DO 91 J = 1,IJUNK
        YCOMP(I) = YCOMP(I) + AA(J)*(X(I)**(J-1))
        IF(X(I) .EQ. 0.0) YCOMP(I) = AA(1)
    CONTINUE

    RMSSUM = RMSSUM + (Y(I)-YCOMP(I))*(Y(I)-YCOMP(I))
CONTINUE

RMS = SQRT(RMSSUM/FLOAT(NITEMS))

5.      PRINT OUT THE RESULTS.

WRITE(7,120)
WRITE(7,120)

```



```

DO 97 I=1,ICOEF
  IJUNK = ICOEF + 1
  DO 97 J=1,IJUNK
    SMATRIX(I,J) = 0.0
  CONTINUE
97 C C

DO 900 N=1,NITEMS
  SUBSUM(I) = 1.0
  DO 98 I=1,IORDER
    SUBSUM(I+1) = XX(N)**(I)
  CONTINUE
98 C

DO 900 J=1,ICOEF
  DO 99 I=1,ICOEF
    SMATRIX(J,I) = SMATRIX(J,I)+SUBSUM(I)*SUBSUM(J)
  CONTINUE
99 C
  SMATRIX(J,ICOEF+1)=SMATRIX(J,ICOEF+1)+SUBSUM(J)*ZZ(N)
  CONTINUE
900 C C

IF(IDIAGN.NE.6) GO TO 22
DO 906 I=1,ICOEF
  IJUNK = ICOEF + 1
  DO 906 J=1,IJUNK
    WRITE(7,110) I,J,SMATRIX(I,J)
  CONTINUE
906 C
22 C
FORMAT(2X,'CURFIT: SMATRIX(' ,I3,' ,',I3,' ) = ',1F15.5)

3. NOW, INVERT THE MATRIX. (SOLVE THE SET OF
SIMULTANEOUS EQUATIONS.)

CALL SOLVE(SMATRIX,ICOEF)

DO 903 I=1,ICOEF
  AA(I) = SMATRIX(I,ICOEF+1)
  IF(IDIAGN.EQ.8) WRITE(7,112) I,AA(I)
  CONTINUE
903 C
FORMAT(2X,'CURFIT: AA(' ,I3,' ) = ',1F15.5)

4. "UNNORMALIZE" THE RETURNED COEFFICIENTS.

```

```

C          DO 901 I=2,ICOEF
          AA(I) = AA(I)/XNORM**(I-1)
901      CONTINUE
C
C          DO 902 I=1,ICOEF
          AA(I) = AA(I) * ZNORM
          IF(IDIAGN.EQ.9) WRITE(7,113) I,AA(I)
902      CONTINUE
113      FORMAT(2X,'CURFIT:  AA(',I3,') = ',1F15.5)
          RETURN
          END
C
C          SUBROUTINE SOLVE(C,NR)
C
C          PURPOSE:  SOLVE A SET OF "NR" SIMULTANEOUS EQUATIONS
C                   USING GAUSSIAN ELIMINATION.
C
C          DOUBLE PRECISION C(100,100),SAVE
C          INTEGER NR
C
C          NC = NR + 1
          DO 303 I=1,NR
            KEXCH = 1
            M = I + 1
            IF(DABS(C(I,I))-1.D-5) 308,308,307
          DO 301 J=M,NC
            C(I,J)=C(I,J)/C(I,I)
          DO 303 J=1,NR
            IF(J-I) 322,303,322
          DO 302 K=M,NC
            C(J,K)=C(J,K)-C(J,I)*C(I,K)
          CONTINUE
          RETURN
C
C          L = I + KEXCH
          IF(L-NR) 309,309,330
308
309
330

```

```

309 DO 311 N=I,NC
      SAVE = C(I,N)
311 C(I,N) = C(L,N)
      C(L,N) = SAVE
      KEXCH = KEXCH + 1
      GO TO 306

      WRITE(7,331)
330 FORMAT(2X,'EQUATIONS CANNOT BE SOLVED...')
331 RETURN
      END

      REAL FUNCTION AMAX(X,NITEMS)
      PURPOSE: FIND THE MAXIMUM VALUE IN AN ARRAY.

      DIMENSION X(500)
      INTEGER NITEMS

      XMAX = X(1)
      DO 340 I=1,NITEMS
        IF (X(I) .GT. XMAX) XMAX = X(I)
      CONTINUE
      AMAX = XMAX
      RETURN
      END

      REAL FUNCTION AMIN(X,NITEMS)
      PURPOSE: FIND THE MINIMUM VALUE IN AN ARRAY.

      DIMENSION X(500)

```

```

C
INTEGER NITEMS
XMIN = X(1)
DO 340 I=1, NITEMS
  IF (X(I) .LT. XMIN) XMIN = X(I)
CONTINUE
AMIN = XMIN
RETURN
END
340

```

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